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Contract No.: NAS 9-12801
Line Item No. 3
DRD No. MA-129T
SHM 20

CR-134201

Space Shuttle Heat Pipe Thermal Control Systems

final report

OCTOBER 1973

GRUMMAN AEROSPACE CORPORATION

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Prepared for

National Aeronautics and Space Administration
Johnson Space Center
Houston, Texas 77058

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R. Haslett, Program Manager

FOREWORD

This report was prepared by Grumman Aerospace Corporation for the Johnson Space Center of the National Aeronautics and Space Administration. The work was done under Contract NAS 9-12801 and was administered by the Thermal Technology Branch of the Structures and Mechanics Division, with Mr. J. Janney serving as Technical Monitor.

The work was performed from June 1972 to October 1973 under the direction of Mr. R. Haslett, program manager and Mr. J. Alario as project engineer. A major contribution was made by Mr. R. Prager in thermal analysis. Contributions were also made by Mr. J. Fiorello in structural design, Mr. E. Leszak in manufacturing methods and Mr. H. Coverly in fabrication. A special tribute is also given to Mr. R. Hembach for his help during the assembly and testing of the heat pipe systems.

ABSTRACT

Three heat pipe (HP) thermal control systems designed for possible space shuttle applications were built and tested under this program. They are: (1) a HP augmented cold rail, (2) a HP/phase change material (PCM) modular heat sink and (3) a HP radiating panel for compartment temperature control. The HP augmented cold rail is similar to a standard two-passage fluid cold rail except that it contains an integral, centrally located HP throughout its length. The central HP core helps to increase the local power density capability by spreading concentrated heat inputs over the entire rail. The HP/PCM modular heat sink system consists of a diode HP connected in series to a standard HP that has a PCM canister attached to its midsection. It is designed to connect a heat source to a structural heat sink during normal operation, and to automatically decouple from it and sink to the PCM whenever structural temperatures are too high. The HP radiating panel is designed to conductively couple the panel feeder HPs directly to a fluid line that serves as a source of waste heat. It is a simple strap-on type of system that requires no internal or external line modifications to distribute the heat to a large radiating area.

This report describes the design details and presents the test results for each of the HP systems and their components. The test results support the feasibility of using HP systems to satisfy shuttle thermal control requirements.

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GLOSSARY

Symbols/Abbreviations

A	area
C_p	specific heat
D	diameter
h	convective heat transfer coefficient, interface conductance
ID	inside diameter
M	mass flow rate
NH_3	ammonia
OD	outside diameter
PCM	phase change material
Q	heat flux
T	temperature
ΔT	temperature change
TC	thermocouple
ϵ	surface emittance
σ	Stefan-Boltzmann Constant
η	fin effectiveness
HP	heat pipe
t	time

Subscripts

c	condenser
CF	Condenser flange
e	evaporator
EF	evaporator flange
f	fin
REJ	rejected
V	vapor
p	plate

Section 1

INTRODUCTION

The heat pipe (HP) is an extremely efficient device for transferring heat with very little temperature drop. Using the processes of evaporation, vapor transport, condensation and return by capillary action, a working fluid transfers heat within a sealed container. In addition to superior thermal performance, HPs have no moving parts, require no electrical power, do not generate noise or vibration, and can be made self-regulating. These are features that make HPs attractive for long-life, high reliability thermal control applications that are frequently needed on spacecraft.

Hardware developed for recent engineering applications of HP technology represents significant advances in the thermal control field (Ref 1, 2 and 3) and flight experiments have demonstrated the ability of HPs to operate predictably in space (Ref 4 and 5). A 1972 evaluation of possible HP applications for the space shuttle orbiter (Ref 6) identified six HP systems as viable alternatives to the corresponding baseline thermal control systems.

Based on these advances and the potential benefits of HPs, a program was initiated by the Johnson Space Center to develop and test prototype hardware for three of the six shuttle HP systems identified in Ref 6.

Section 2

SUMMARY

The main objective of the program was to determine the feasibility of three HP thermal control systems by developing prototype hardware and demonstrating its thermal performance under shuttle-type environments. The following three HP systems were evaluated:

- HP/phase change material (PCM) modular heat sink
- HP radiating panel for compartment temperature control
- HP augmented cold rail

The development sequence for each of the three HP thermal control system consisted of three phases: (1) detailed design, (2) thermal bench testing of the component HPs, and (3) thermal tests of the assembled system. In addition, after the initial bench tests, a representative HP from each system was subjected to a vibration loading equivalent of 100 shuttle missions and rechecked to determine if any performance degradation had occurred.

All of the HPs were of spiral artery design with fine circumferential wall grooves to provide superior performance and facilitate ground testing. Spiral artery pipes readily self-prime in a 1-g field, thus minimizing puddling effects and sensitivity to gravity. The fine wall grooves improve the internal film heat transfer coefficients thereby minimizing the overall temperature drop across the heat pipe.

HP/PCM Modular Heat Sink

The modular heat sink system provides a self-regulating heat sink for cold-plate-mounted equipment located outside a spacecraft pressure shell. It was designed to limit the temperature of a simulated equipment baseplate to 160°F, with a continuous 40-watt power dissipation and a varying structural sink temperature. The system consists of a diode HP connected in series to a standard transport HP that has a phase change material (PCM) canister attached to its midsection. During

normal operation (structure temperature between -40°F and 110°F) the baseplate is coupled directly to the structural sink via the transport and diode HP connection. When the structure becomes too hot to function as an acceptable sink, the diode reverses and the baseplate is connected to the PCM sink.

Each component HP was successfully bench tested before being incorporated into the system. The diode's forward-mode capacity varied between 20 and 60 watts, depending on sink temperature and it quickly shut off when its condenser temperature was raised above its evaporator temperature. There was also little apparent performance degradation resulting from the vibration loadings. The transport HP demonstrated a 150-watt capability with an 80-watt-hour storage capacity for its PCM canister.

The system test results for the normal steady state mode verified a 40-watt capacity over a -40 to 110°F operating range, while holding the simulated equipment baseplate to less than 140°F. Transient operation (PCM melting) was successfully demonstrated in both 1-g ground tests and a 3-g centrifuge test that duplicated the entry inertia field.

HP Radiating Panel

The HP radiating panel represents a simple method for utilizing available fluid waste heat sources to supply energy for on-orbit thermal control of shuttle compartments. It is part of an integrated thermal control system concept for coupling areas that require cooling, with those areas that need additional heat to maintain acceptable temperatures. In this case, the waste heat source is hydraulic fluid and the radiating panel is typical of one that could be used to maintain a -20°F minimum temperature for the main landing gear compartment. The panel consists of six feeder HPs and a radiating fin. The interface between the HP panel and the hydraulic line is a simple clamp-on connection that requires no internal or external fluid line modifications.

Each feeder HP was bench tested to at least 150 watts at .5-in. adverse tilt. One of the pipes was tested in both a straight and L-shaped configuration with no detectable difference in performance. However, postvibration tests indicated that the

artery had been damaged, as witnessed by decreased heat transport capacity and increased temperature difference between evaporator and condenser. But performance was still within acceptable limits.

After assembly, the HP radiating panel was tested in a thermal vacuum chamber that had controllable termperature cold walls. The results of these system tests proved that a HP radiating panel can be used to extract waste heat from a fluid line through a simple mechanical bolted connection that has minimum impact on the fluid system. In general, the HP panel extracted between 50 and 120 watts from the hydraulic fluid, with a 60 to 90°F inlet, and rejected it to the -40 to 0°F enclosure.

HP Augmented Cold Rail

Placing the HP in the center of a simple fluid rail, surrounded by the two standard fluid passages, increases the rails local power density capability by diffusing localized heat inputs over the entire length of rail.

A 24-in. long cold rail was built and tested using a water HP, to meet non-toxicity requirements, and provide high performance. All heat pipe components were made of copper and treated with an Ebonol-C coating to enhance the wettability of the surfaces. The copper tube, which formed the envelope of the heat pipe, was force fitted into an aluminum extrusion that made up the main body of the rail. During bench tests, the water HP demonstrated a 350-watt postvibration capacity – presenting a slight degradation from earlier bench tests.

For system testing, aluminum heater plates were bolted to the flanges of the cold rail to simulate the interface with flange-mounted equipment boxes. Test results demonstrated that an equipment flange root temperature of 140°F can be maintained with localized power dissipation as high as 45 watts/in. (over 2 in.) while the remainder of the rail receives 6 watts/in. With the HP rendered non-operational, results showed only marginal performance degradation – a flange root temperature rise of only 4°F. This small difference in performance was not due to the HP – it worked properly; but was due to the basic design of the cold rail which did not take full advantage of the HP's capability.

Section 3

HP/PCM MODULAR HEAT SINK SYSTEM

The HP/PCM modular heat sink system is designed to provide autonomous thermal control of electrical power dissipating equipment located in remote portions of the shuttle vehicle, outside of the pressure shell. It eliminates long fluid cooling lines, with their inherent installation and leak problems.

The system couples the electronics base plate (heat source), via HPs, to either a structural or PCM heat sink, as required. During most phases, heat would normally be transferred to the structure, but, when the structure is at a high temperature, the pipes decouple from the structure and utilize the PCM sink for equipment cooling.

As shown in Fig. 3-1, the HP/PCM modular heat sink consists of a cold plate which interfaces with electronics, a transport HP whose evaporator is integral with the cold plate, a PCM container attached to the middle of the transport pipe, and a diode HP that connects the transport pipe to the structure. During boost and the entire on-orbit operation, the baseplate is coupled directly to the structural sink (average temperature -40°F to +110°F) through the transport and diode HP connection. During entry, the structure becomes too hot to function as a sink ($T \approx 200°F$) and the diode reverses, decoupling the structure from the transport pipe. This creates an isolated system consisting of the base plate, transport HP and PCM container with the heat flow path terminating at the PCM. When the structure cools, the diode once again completes the connection to it and allows the liquefied PCM to unload its stored energy.

3.1 DESIGN DETAILS

3.1.1 Requirements

The HP/PCM modular heat sink system was designed for the following nominal requirements.

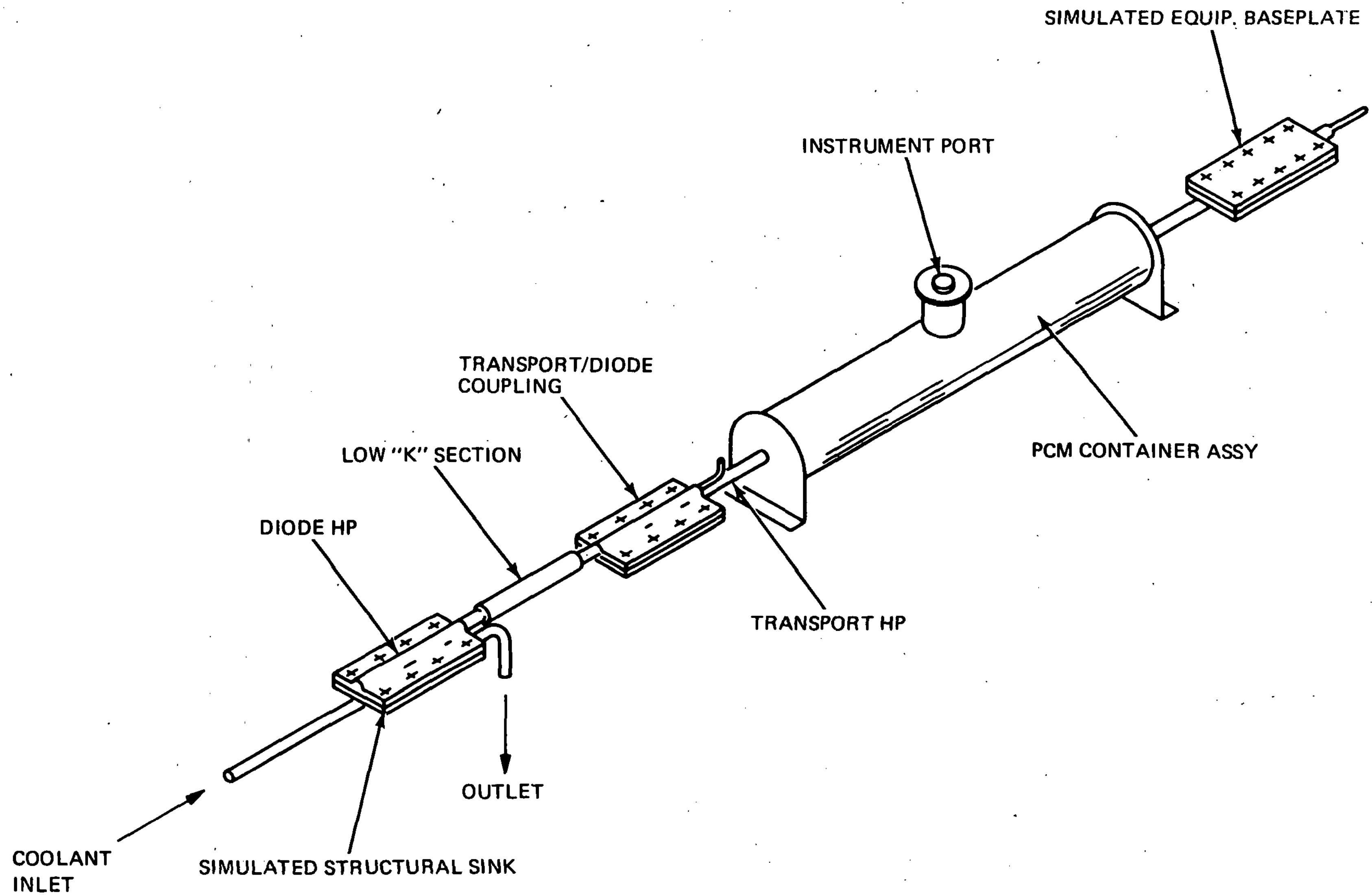

Fig. 3-1 HP/PCM Modular Heat Sink System

- System
  - Operating heat load = 40 watts
  - Maximum simulated equipment baseplate temperature = 160°F
  - Simulated structure temperature range = -40 to 110°F
  - Overall length = 40 to 60 in.
- Diode HP
  - Maximum operating load = 80 watt @ 80°F
  - Reverse heat flow $\leq$ 2 watts
  - Condenser temperature range between -40 and 100°F
- Transport HP
  - Maximum evaporator temperature = 160°F
  - Operating load = 40 watts
- PCM Canister
  - Storage capacity = 80 watt-hours
  - PCM melt range between 120 and 140°F

In addition, the system was required to function (reflux mode) in a 3-g inertial environment with a 200°F structural sink, to simulate shuttle entry conditions.

All attachments and couplings were to be made through realistic interfaces. At the heat source, this was done by attaching electrical heater ribbon to one face of an aluminum plate (simulated equipment baseplate) and bolting the other face to the flanged evaporator section of the transport HP. At the sink, the flanged condenser of the diode HP was bolted to a heavy-gauge aluminum cold plate to simulate the attachment to structure.

3.1.2 Diode HP

Figure 3-2 shows the overall configuration and design details for the diode HP. The diode has 6 in. long evaporator and transport sections and an 8-in. long condenser that also includes a 2-in. reservoir section. The evaporator and condenser sections

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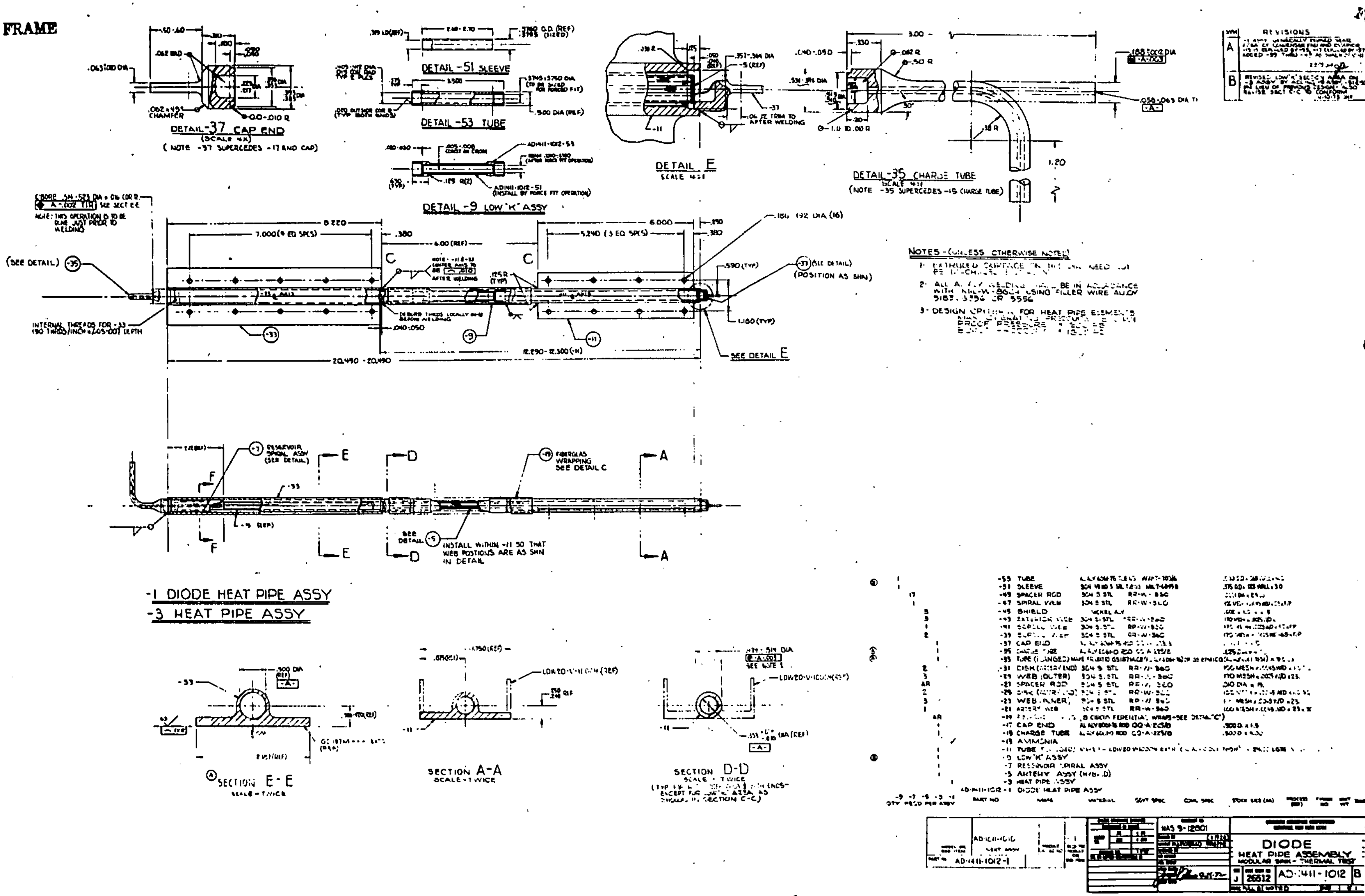

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Fig. 3-2 Diode HP Assembly Drawing
(Sheet 1 of 2)

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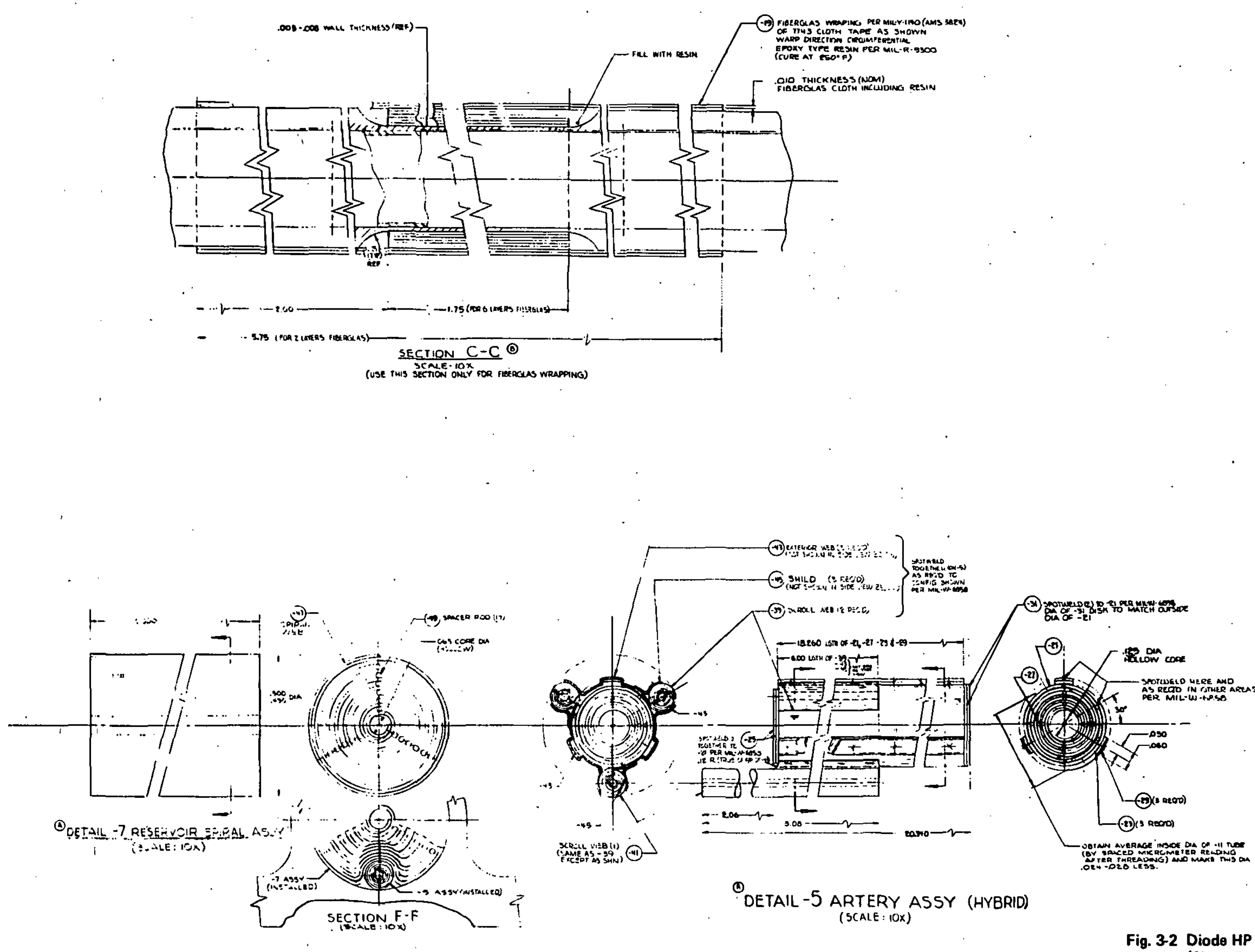

Fig. 3-2 Diode HP Assembly Drawing (Sheet 2 of 2)

are machined from standard aluminum extrusions; a flanged .333-in. ID section for the evaporator and a flanged .500-in. ID section for the condenser/reservoir.

The diode HP, which acts as the on/off switch for the system, operates on the liquid blockage principle, wherein the diode stops functioning as a normal HP when excess fluid held in the reservoir at the condenser end is released and transported to the evaporator. At the evaporator, the excess fluid fills the vapor space and 'chokes' the pipe. The reservoir is sized to hold sufficient fluid to completely block the vapor space throughout the evaporator and transport sections. To test diode operation in a 1-g environment, it is necessary to restrict the vapor space gap to a dimension that will self-fill under surface tension forces.

To minimize heat flow from the condenser to the evaporator during the shutoff mode, a low thermal conductivity (low-k) section is built into the transport section. The low-k section consists of a .333-in. ID stainless steel tube press fitted into an aluminum outer envelope which is welded to the evaporator and condenser sections. The aluminum sleeve is necked down to a .007-in. wall thickness and then overwrapped with fiberglass to strengthen it. The total thermal conductance of the section is calculated to be .00955 watt/°F which gives a .73-watt reverse mode heat flux for the design ΔT of 77°F.

The conventional liquid blockage design (Ref 7) calls for normal HP operation at a single operating temperature, or, at worst, over a very restricted temperature range. In contrast, the diode in the modular heat sink system must operate over a relatively wide, 150°F, operating range. Because of this, its reservoir actually functions more as an expansion chamber to accommodate excess fluid not needed during normal HP operation at the upper end of the temperature range (110°F). Due to expansion and contraction of ammonia, a 100% charge at one temperature results in an overfill condition at higher temperatures and an underfill condition at lower ones. Because of the nearly 2-gram variation in the theoretically optimum charge over the operating temperature range (see Fig. 3-3), no additional fluid charge is needed to insure a blocked vapor space in the reverse mode. The needed fluid is already in the pipe to accommodate the normal low temperature operating requirements.

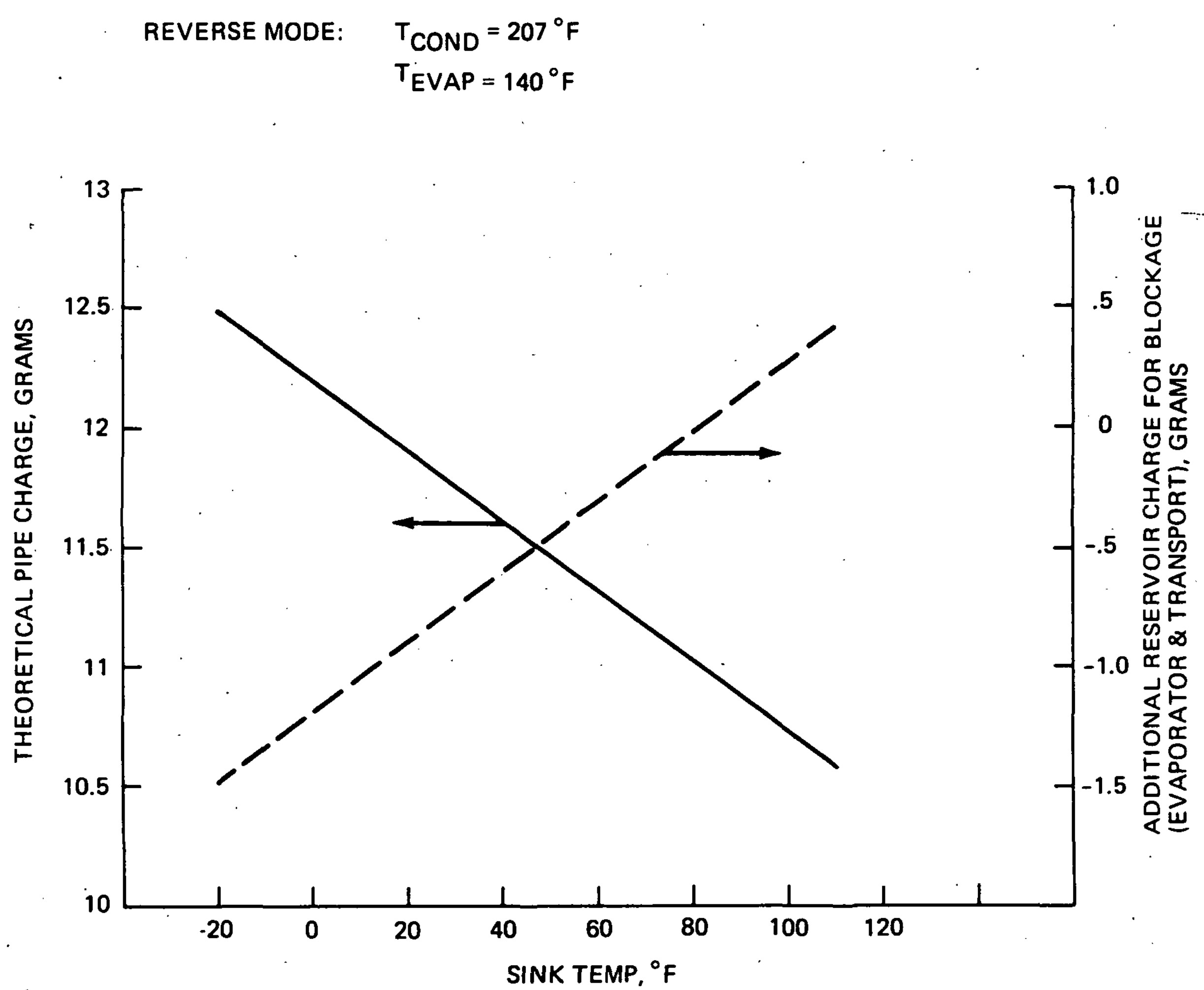

Fig. 3-3 Diode HP Charge Requirements

The design details contained in Fig. 3-2 are summarized below:

Envelope

- Material = Aluminum 6061-T6

	Evaporator	Transport	Condenser	Reservoir
• ID, in.	.333	.333	.500	.500
• OD, in.	.500	.390	.625	.625
• Length, in.	6	6	6	2

- Grooves: circumferential, 150/in.
- Working fluid = ammonia (charge = 16.6 grams)

Wick

The diode uses a spiral artery/tunnel wick with three retainer legs. It is designed to provide a .014-in. vapor gap (evaporator and transport sections) between the artery OD and the pipe wall to permit self-filling during reverse mode operation in 1-g. The vapor gap in the condenser section is larger (.10 in.) to preclude inadvertent surface tension priming of the condenser vapor space during the normal operating mode.

The reservoir wick uses spiral wraps of 100/100 mesh screening with a .020-in. gap between spirals. This provides small enough capillaries to insure that any excess fluid will accumulate in the reservoir section and not in the condenser vapor space. The reservoir gap is also larger than the .010-in. gap in the main artery to avoid trapping and holding fluid inventory that belongs in the working artery. Communication between the main artery and the reservoir is provided by extending one of the artery legs and spot welding it to the outer wrap of the reservoir screening.

- Material = 100/100 mesh stainless steel screen
- Artery OD = .297 in.
- Tunnel Core Dia. = .125 in.
- Vapor Space = .014 in. (evaporator, transport)
  .100 in. (condenser)

- Spiral Gap = .020 in. (reservoir), .010 in. (main artery)
- Retainer legs = 3

The major diode components are shown before assembly in Fig. 3-4. The condenser section of the artery showing the connection to the screened reservoir is given in Fig. 3-5.

Predicted Performance

The predicted heat transport capacity of the diode in the normal operating mode varies from 40 to 85 watts over its -40 to 110°F operating temperature range. (See Fig. 3-6.)

3.1.3 Transport Heat Pipe

The transport HP uses ammonia as the working fluid, a circumferentially grooved extruded aluminum envelope and a spiral artery/tunnel wick. The evaporator and condenser sections are formed from flanged aluminum extrusions. The midsection of the HP contains the PCM canister and is joined to the flanged end-sections by seam welds.

The design details for the transport HP are given in Fig. 3-7 and are summarized below:

Envelope

- Material = Aluminum 6061-T6
- ID = .500 in.
- OD = .625 in.
- Lengths
  - evaporator = 7 in.
  - condenser = 6 in.
  - PCM Canister = 20.6 in.
  - Adiabatic Sections (2) = 4 in. each
  - Overall = 41.6 in.
- Grooves: circumferential, 150/in.
- Working Fluid = Ammonia (Theoretical charge = 33.8 grams)

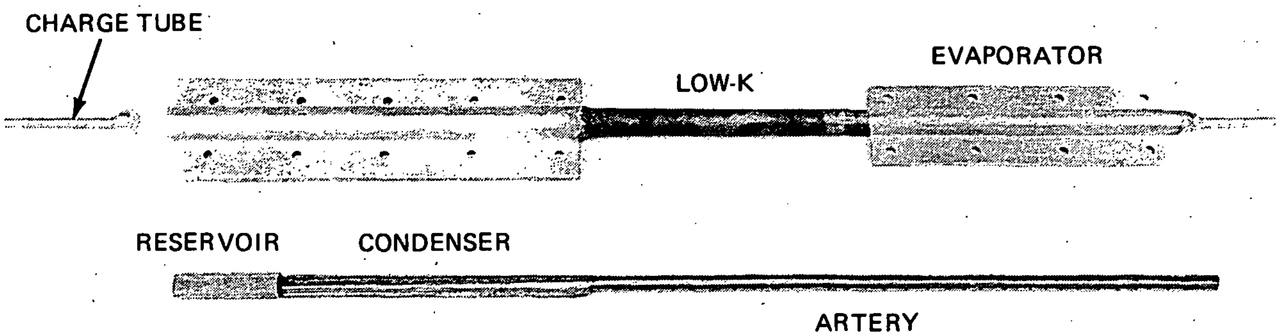

Fig. 3-4 Diode HP Assembly

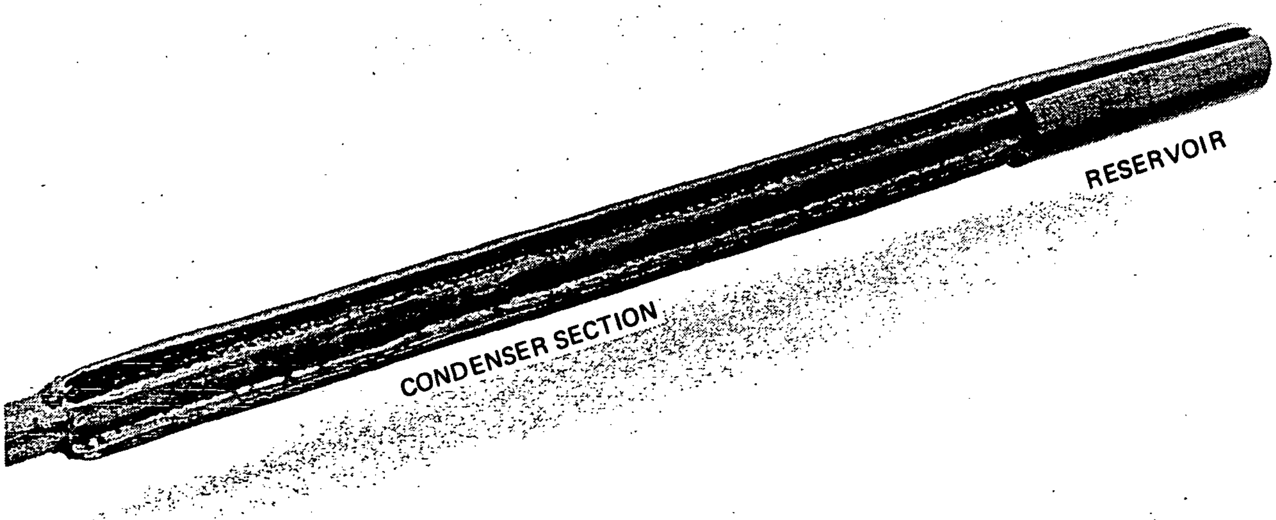

Fig. 3-5 Diode Artery, Condenser/Reservoir

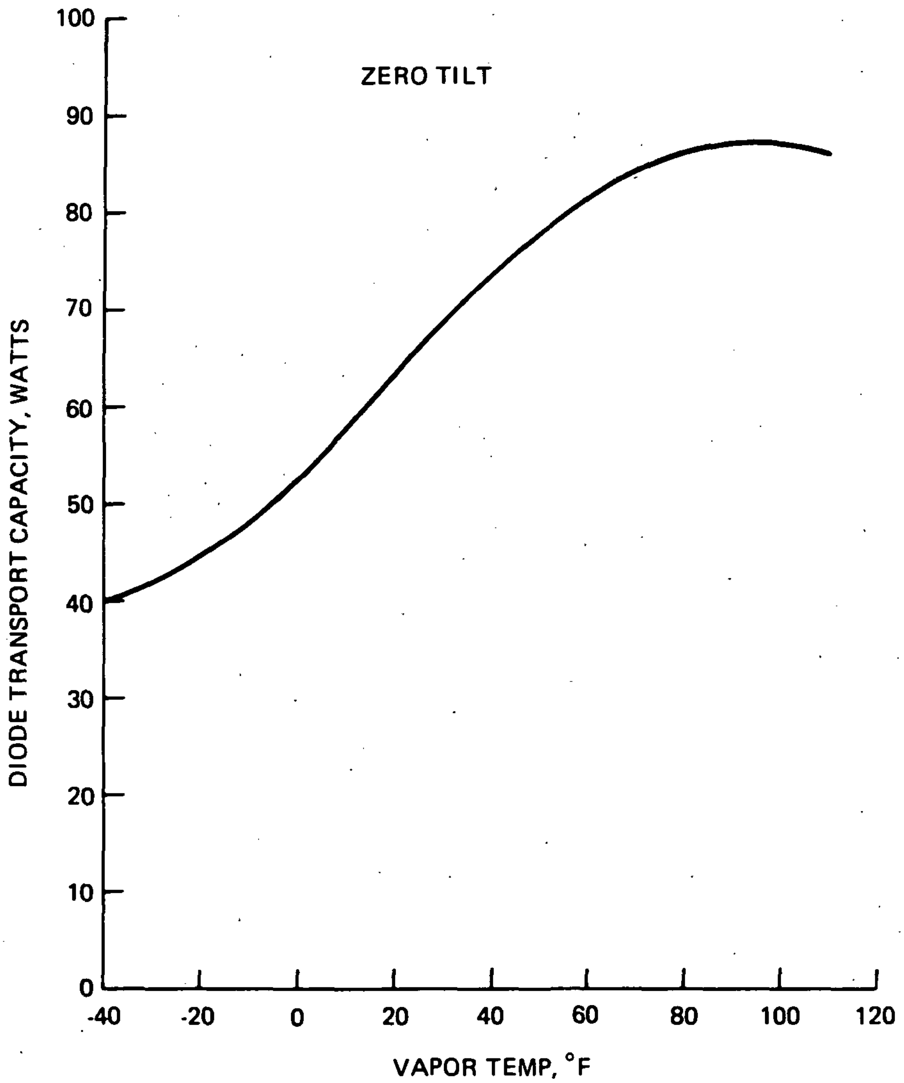

Fig. 3-6 Diode HP Predicted Normal Mode Performance

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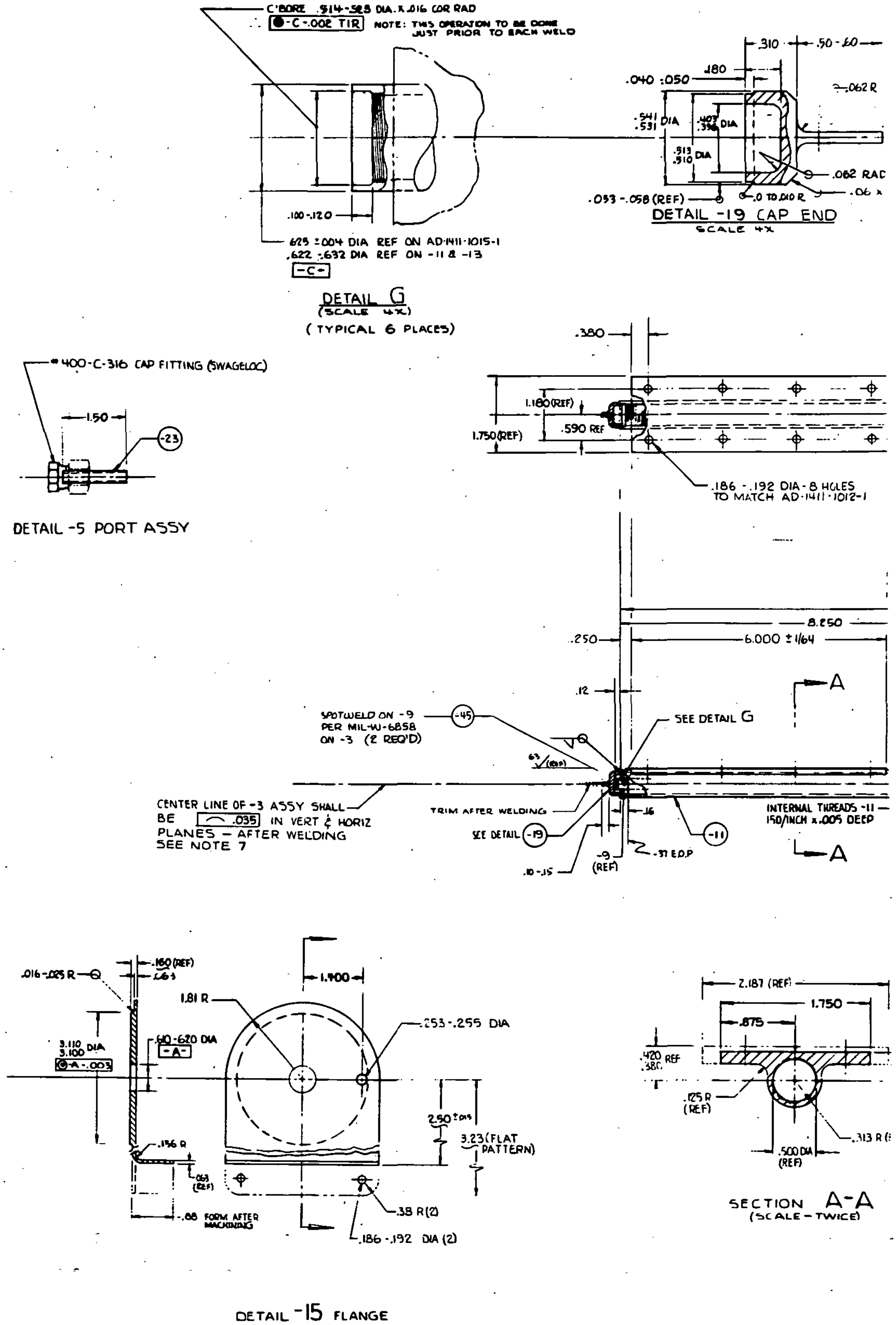

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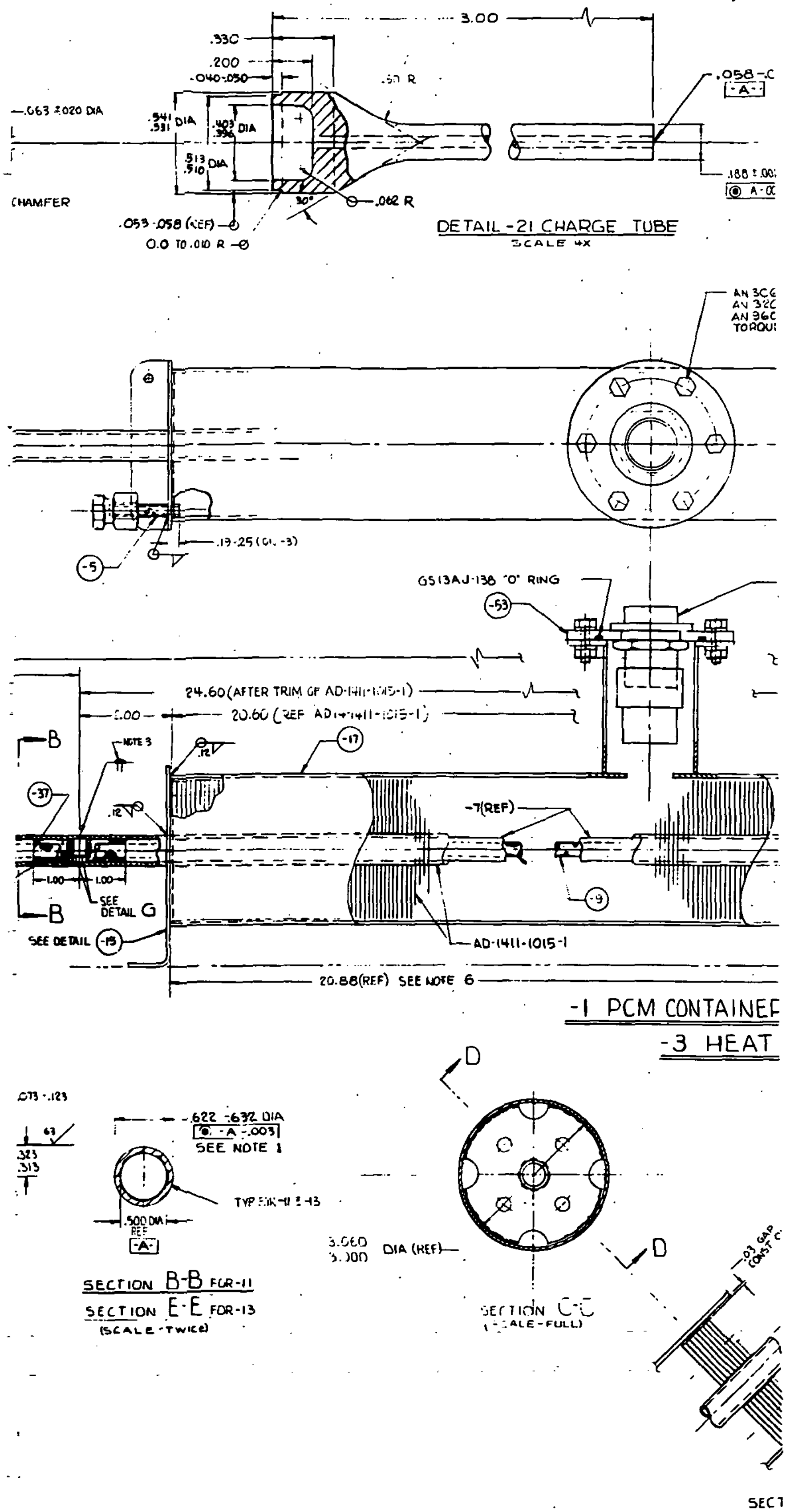

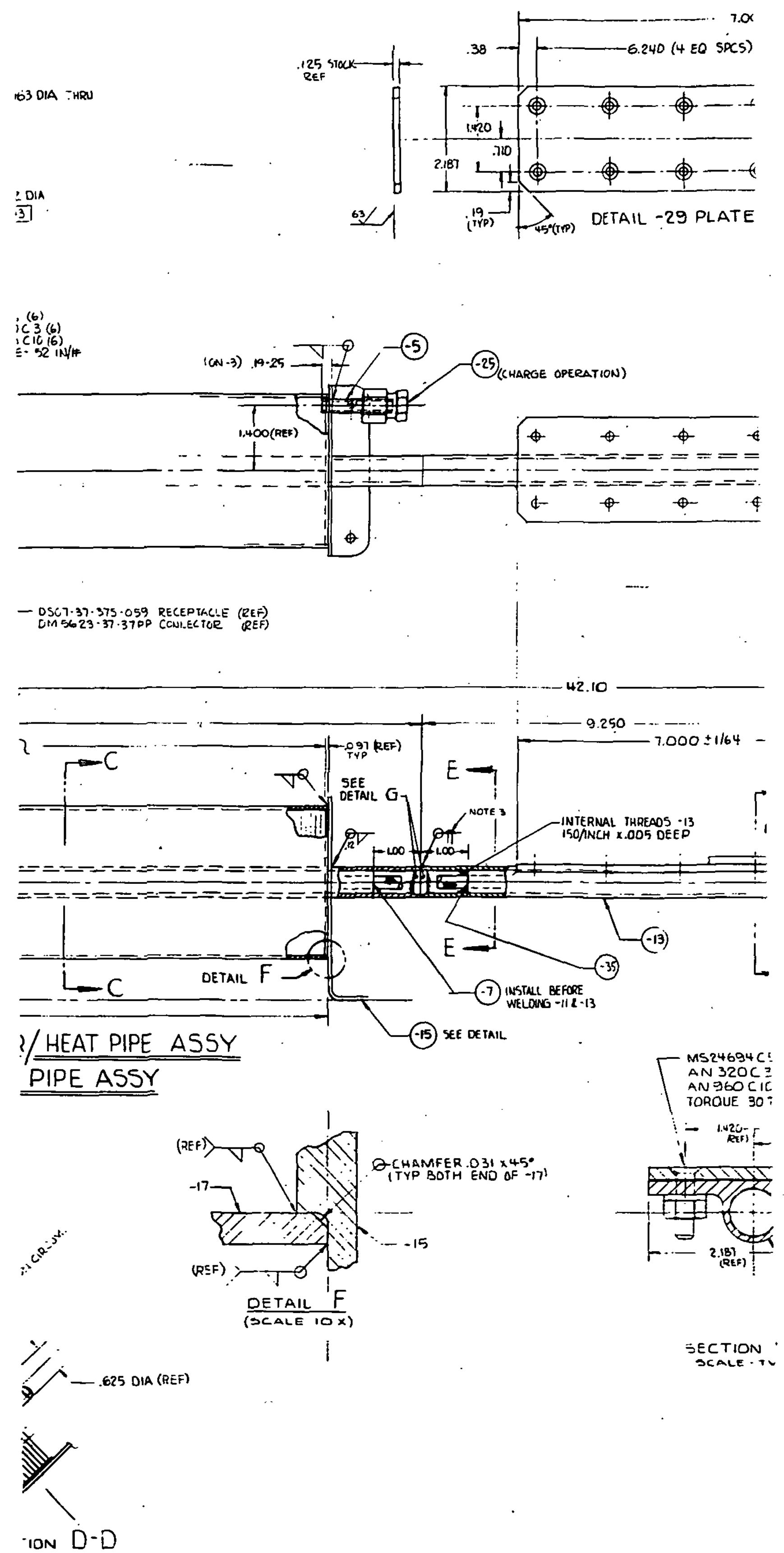

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2.187
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45°(TYP)
DETAIL -29 PLATE
(CHARGE OPERATION)
1.400(REF)
DS07-37-375-059 RECEPTACLE (REF)
DM5623-37-37PP CONNECTOR (REF)
42.10
9.250
7.000 ±1/64
.097 (REF) TYP
SEE DETAIL G
NOTE 3
INTERNAL THREADS -13 150/INCH x.005 DEEP
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DETAIL F
INSTALL BEFORE WELDING -11 & -13
SEE DETAIL
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AN 320C3
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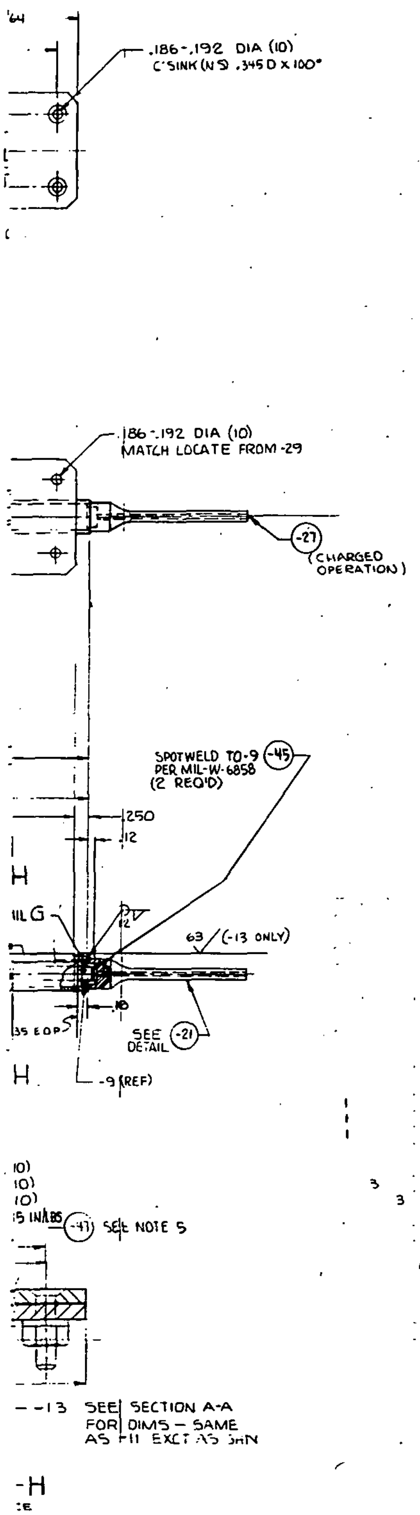
SECTION D-D



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   c- -17 COVER
   d- -15 FLANGE (CLOSIN
   e- INSTALL -7 RET
   f- -11 TUBE (OR)
   g- -13 TUBE
   h- -5 PORT ASSY (2
   j- INSTALL -35, -
   k- -19 CAP END
   l- -21 CHARGE END

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								-35	RETAINER ASSY
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			1					-31	ARTERY WEB
							1	-29	PLATE A
							✓	-27	AMMONIA
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REVISIONS

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LOK® MFG BY CRAWFORD FITTING CO., SOLON, OHIO (44139)

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L ALY 6061-T4 SH,	QQ-A-250/11		.190 x 4.0 x 4.0	NONE	NONE		
L ALY 6061-T4 SH	QQ-A-250/11		.125 x 4.0 x 4.0				
L ALY 6061-T6 TUBING	WW-T-700/6		2.000 D x 065 WALL				
L ALY 6061-T6 TUBING	WW-T-700/6		3.250 D x 065 WALL x 22.0	NONE	NONE		
DC-340		MFG BY DOW-CORNING					
304 S. STL	RR-W-360		100 MESH x .0045 W/D	NONE	NONE		
304 S. STL	RR-W-360		100 MESH x .0045 W/D				
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304 S. STL	RR-W-360		100 MESH x .0045 W/D				
L ALY 6061-T6 SH	QQ-A-250/11		.125 x 2.5 x 7.5				
L ALY 6061-T6	WW-T-700/6		.250 D x .035 WALL x 2.0				
L ALY 6061-0 ROD	QQ-A-225/8		.750 D x 4.00				
ALY 6061-T6 ROD	QQ-A-225/8		.750 D x 1.25				
ALY 6061-T6 SH	QQ-A-250/11		.160 x 4.0 x 6.0				
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G5187MICE (AL ALY 6061-T6) OR G5187MICG (AL ALY 6061-T6511)			x 10.0 LGTH				
SY				NONE	NONE		

	CONTRACT NO. NAS 9-12801	GRUMMAN AEROSPACE CORPORATION BETHPAGE, NEW YORK 11714
	DRAWN BY J. FIORELLO	PCM CONTAINER / HEAT PIPE ASSEMBLY MODULAR SINK - THERMAL TEST
		SIZE J · CODE IDENT NO. 26512 · AD-1411-1011
		SCALE FULL · NOTED

Fig. 3-7 Transport HP and PCM Container Assembly (Sheet 1 of 2)

FOLDOUT FRAME 1

FOLDOUT FRAME 2

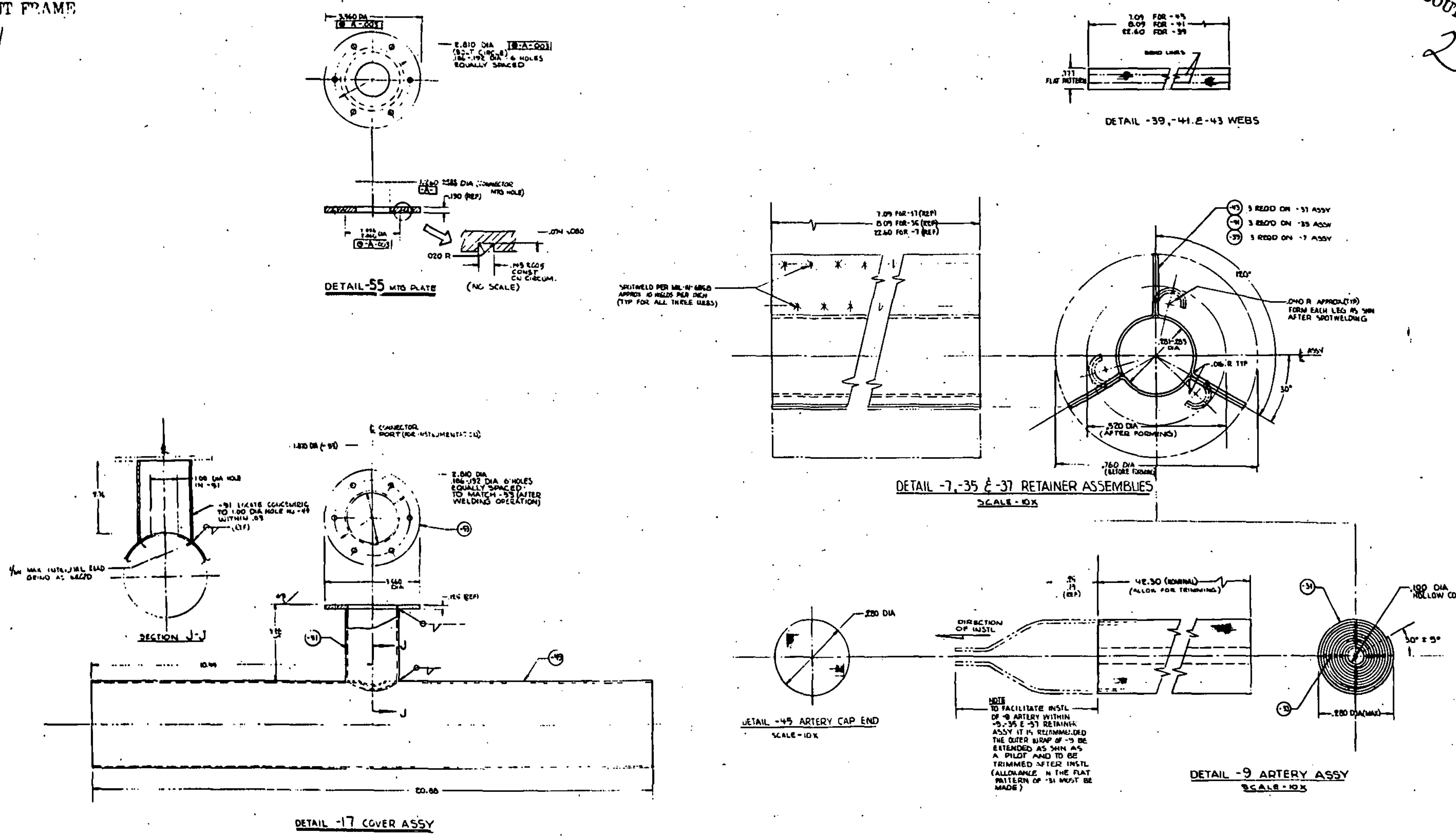


Fig. 3-7 Transport HP and PCM Container Assembly (Sheet 2 of 2)

Wick

- Material = 100/100 mesh stainless steel screen
- Artery OD = .313 in.
- Retainer OD = .328 in.
- Tunnel Core Dia. = .093 in.
- Spiral Gap = .010 in.
- Retainer Legs = 3

Predicted Performance

The predicted capacity of the transport HP, based on a 100% fluid charge at each operating temperature, varies from 501 watts to 162 watts over a -20 to 140°F range. (See Figure 3-8.) However, to achieve a 100% fill at all temperatures an excess fluid reservoir is needed to accommodate fluid expansion at higher-than-fill-point operating temperatures.

Due to the expansion and contraction of the working fluid in a normal HP (without an excess-fluid reservoir), a 100% fill at a given temperature results in an overfill condition at higher temperatures and an underfill at lower temperatures. For the overfill condition, excess fluid would accumulate at the colder condenser end, occupy some of the vapor space and effectively block off a portion of the condenser. The length of condenser which would be blocked depends on the condenser vapor space volume and the amount of excess fluid. On the other hand, a fluid deficiency caused by a fluid contraction would result in a degraded heat transfer capacity due to a partially starved wick. The tunnel would be the first to lose its fluid while the spiral remains completely filled. The fluid lost by the tunnel serves to replenish the spiral portion of the artery as the temperature decreases. This situation would prevail until the spiral needs more fluid than what is available. At this point the capacity of the spiral degrades with decreasing temperature due to its underfilled condition.

Figure 3-9 shows the charge requirements (for a 100% fill) as a function of operating temperature for the transport HP. The charge needed to fill only the spiral portion of the artery (tunnel empty) is also shown. There is a 6.2-gram variation in required charge between temperature extremes. By selecting the fill point at 75°F (33.8 grams) the HP can provide a minimum 65-watt capacity over the design range

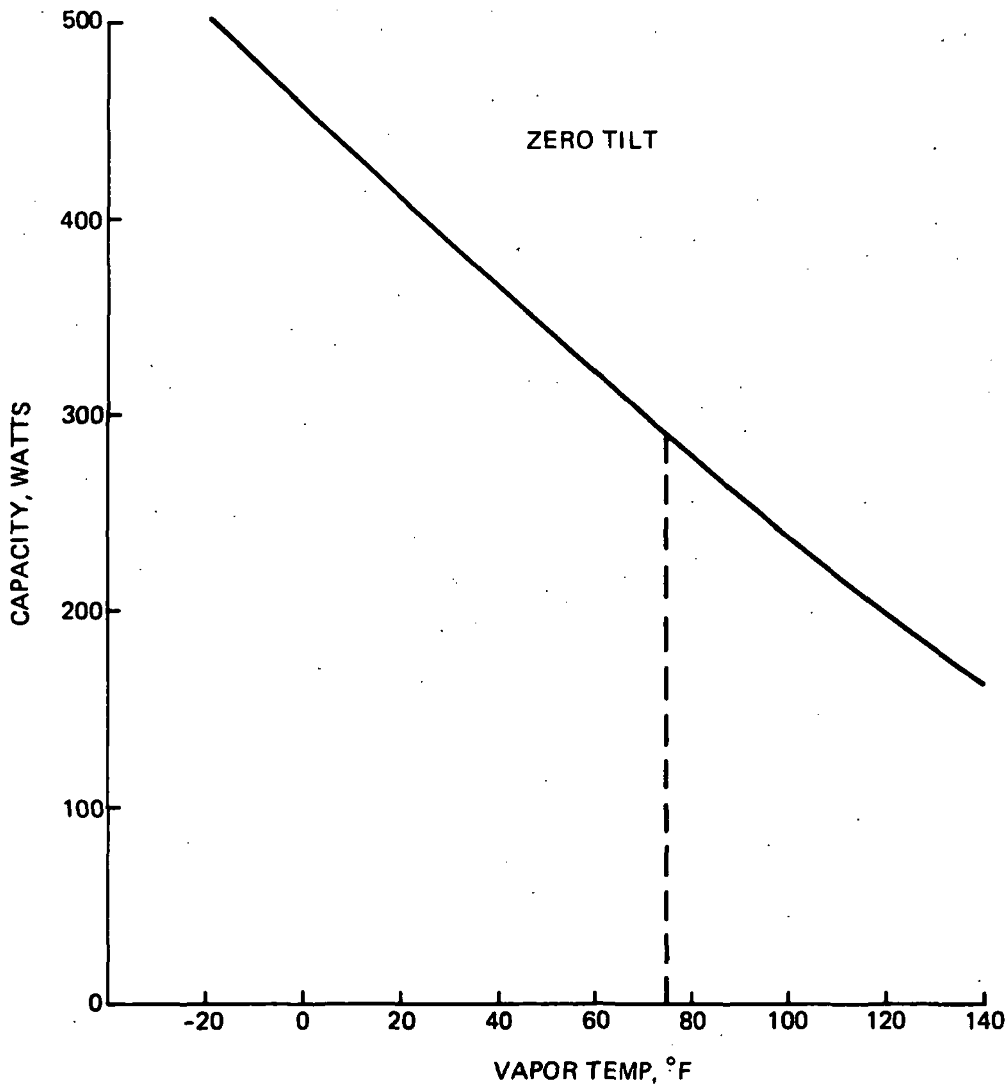


Fig. 3-8 Predicted Transport HP Performance, 100% Charge at All Temperatures

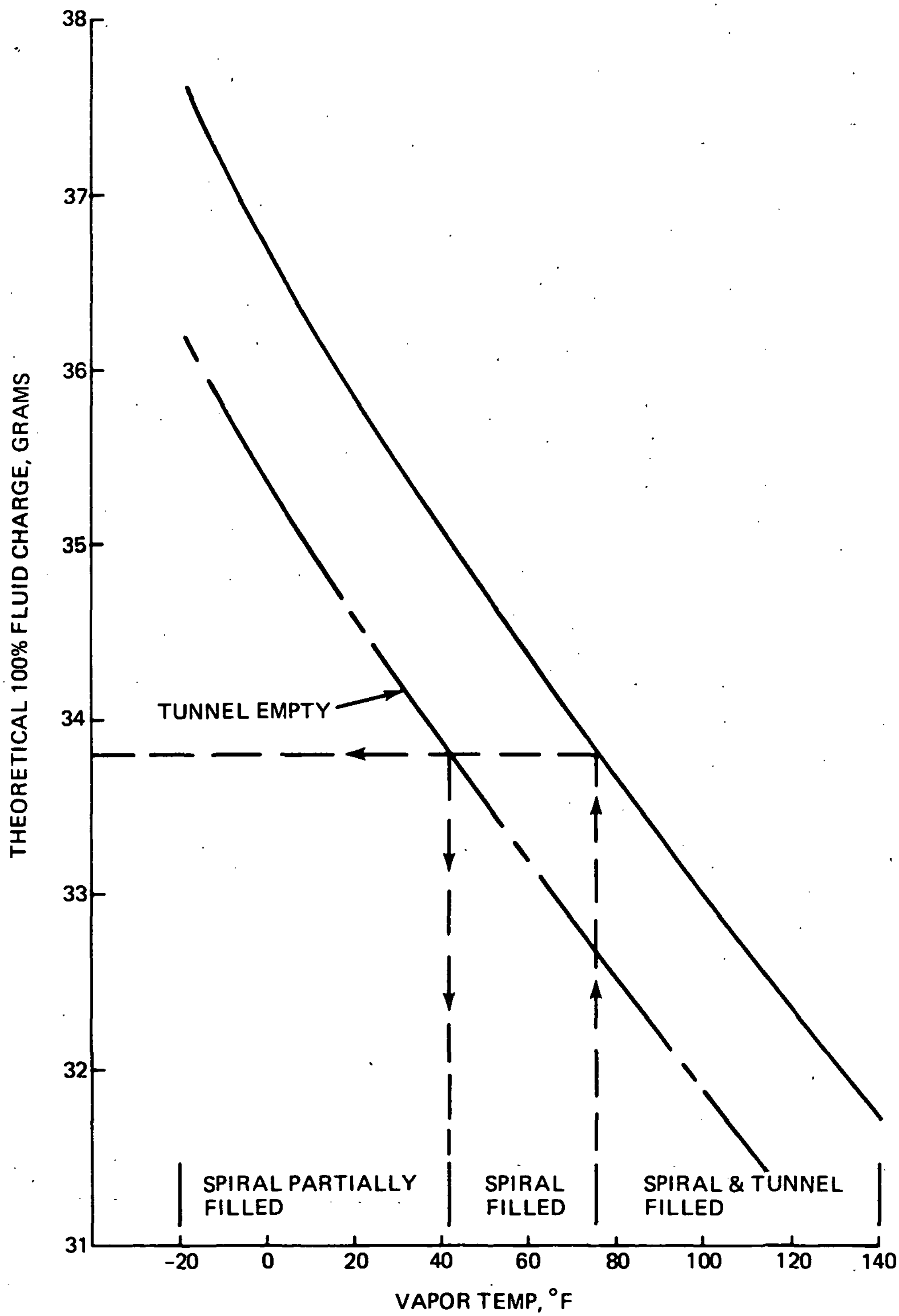


Fig. 3-9 Transport HP Required NH_3 Charge vs Temperature

without the need for an excess fluid reservoir. This is illustrated in Figure 3-10 where curve (B) shows the predicted capacity and accounts for degraded performance at the underfilled conditions (below 75°F).

Between 40 and 75°F, the tunnel is empty but the spiral is completely filled. Below 40°F, the capacity of the spiral degrades with decreasing temperature in the manner shown in curve (A), which shows the capacity degradation of the spiral as a percentage of the 100% fill value. With both the spiral and tunnel filled (75 to 140°F), the capacity varies from 287 watts to 165 watts. When only the spiral portion is filled (40 to 75°F) the capacity varies between 178 watts and 142 watts. When operating with a partially filled spiral the capacity falls from 178 watts (at 40°F) to 65 watts at -20°F.

At points above 75°F, a proportional length of the 6-in. condenser section will be blocked, up to a maximum of 2.15 in. which occurs at 140°F. However, the maximum permissible blocked length is 4.48 in. – a condition that would result in a 25 watt/in.^{2} power density (the self-imposed design limit) at the required 40-watt heat load.

The transport heat pipe/PCM assembly is shown in Fig. 3-11.

3.1.4 PCM Canister

Design details for a PCM canister with an 80 watt-hour storage capacity and a PCM melt range between 120 and 140°F are contained in Fig. 3-7.

The basic canister design uses .016-in. thick circular aluminum fins (10 fins/in.) that are brazed to the OD of the transport HP and serve to insure uniform heat transfer within the PCM by providing highly conductive transfer paths. This is necessary because PCM's have very low thermal conductivities, which would result in very steep temperature gradients at the HP wall. The circular fins contain notches and holes to allow even distribution of the PCM within the canister. They also serve as conduits for the internal thermocouple instrumentation. In addition, the fin surface is dimpled to increase the effective area in contact with the PCM.

The PCM itself is myristic acid, a mild organic acid, with a melting point of 135°F and a heat of fusion of 86 BTU/lb. In selecting the PCM, it was important to get a

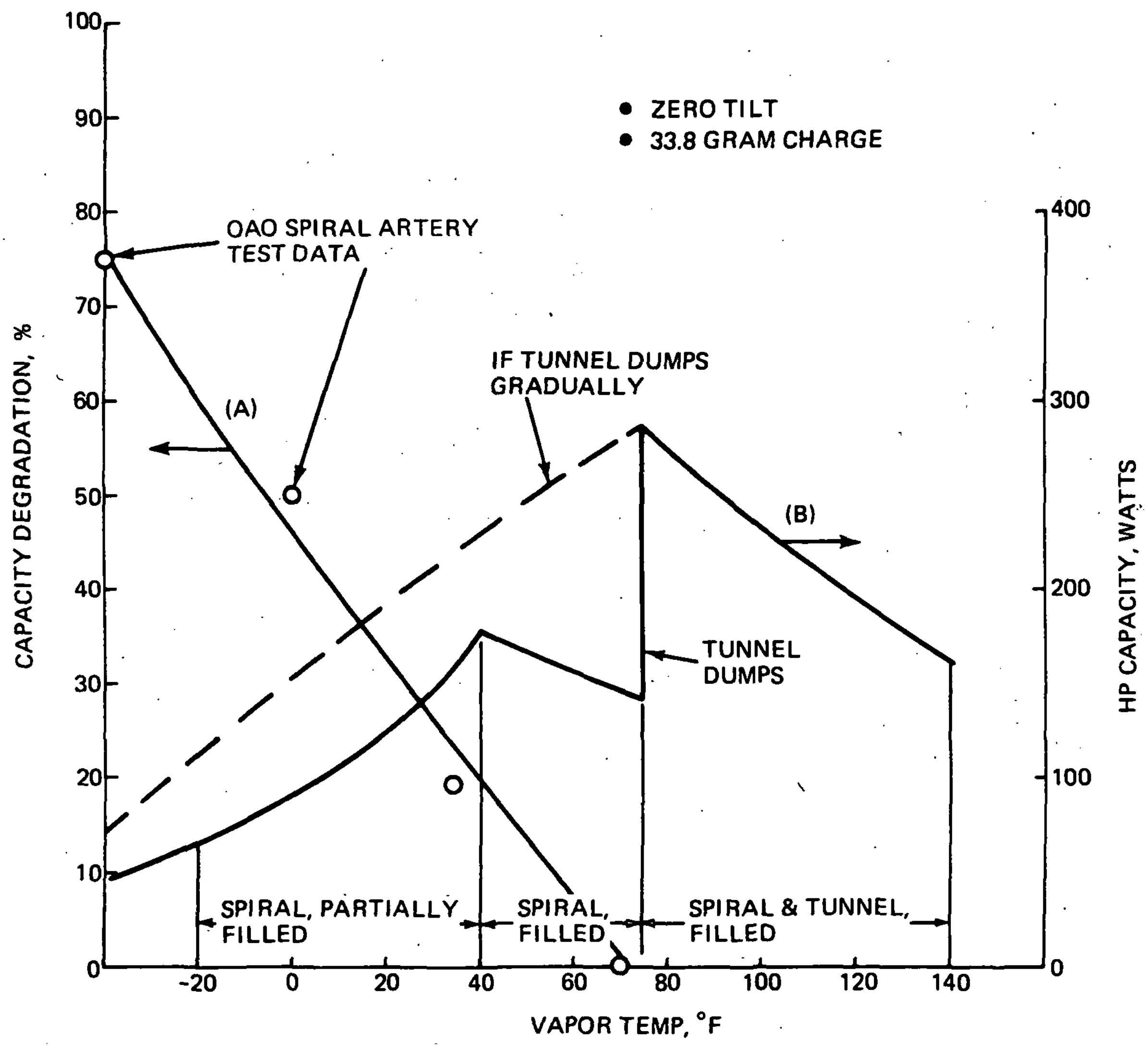


Fig. 3-10 Predicted Transport HP Performance, 100% Charge at 75°F

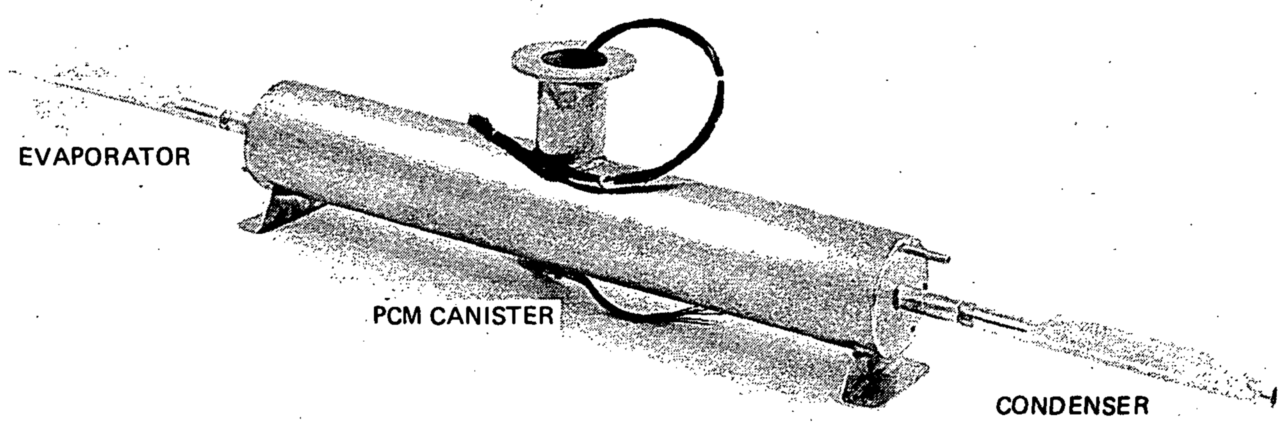


Fig. 3-11 Transport HP/PCM Assembly

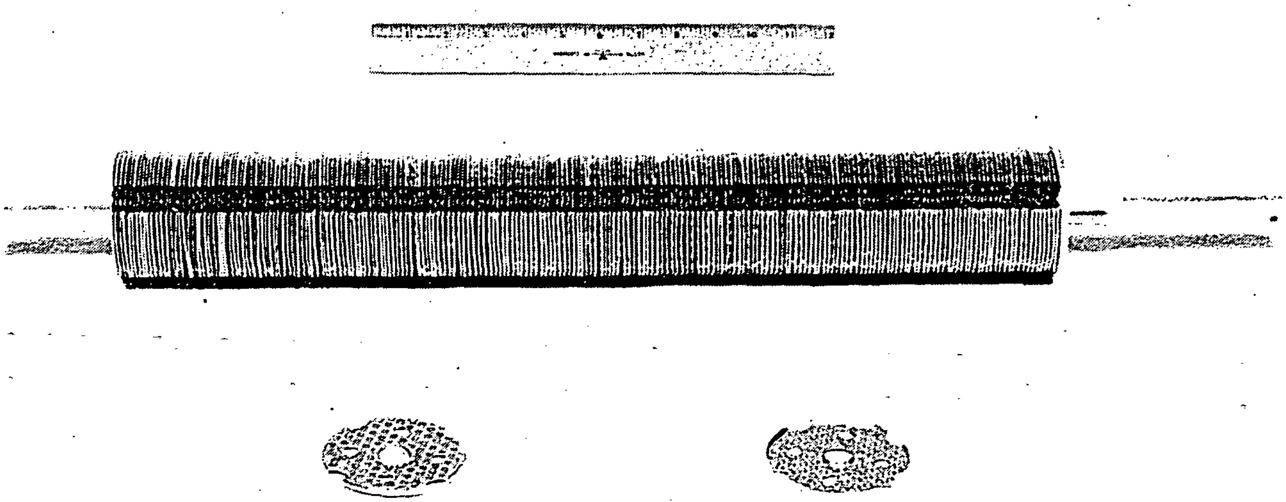


Fig. 3-12 PCM Fin Assembly

melt temperature that was low enough to keep the equipment baseplate temperature below its maximum design value and yet high enough to exceed the vapor temperature of the transport HP during normal operation. Appendix B contains the method used to determine the canister size and the number of fins/in.

Figure 3-12 shows the PCM fin assembly after the aluminum fins were brazed to the center portion of the transport HP but before the flanged end sections were seam welded on.

3.2 COMPONENT BENCH TEST RESULTS

Thermal bench tests were conducted for each component HP to verify acceptable performance before being incorporated into the modular heat sink system. The diode HP was also subjected to vibration loadings equivalent to 100 shuttle missions and then rechecked to determine the resulting performance degradation.

3.2.1 Diode HP

Figure 3-13 shows the setup and instrumentation of the diode during bench testing. It was instrumented with 16 copper/constantan thermocouples; the thermocouple numbers correspond to those used during the system testing. During the normal HP mode (forward mode) testing, heat was applied to the evaporator flange using nichrome heater ribbon and coolant fluid was supplied to the structural sink simulator (cold plate) attached to the condenser flange. Water was used as the coolant for the moderate sink temperatures (55°F to 110°F) and Freon-12 refrigerant for sink temperatures below 55°F. For reverse mode testing (diode 'off'), the cold plate was drained of fluid and heat was applied to the condenser flange using nichrome heater ribbon that was attached to it. Armaflex rubber insulation was used to insulate the diode from its surroundings.

The diode was first tested in the forward mode at various heat loads, sink temperatures and adverse tilts to determine its performance characteristics. Adverse tilt is defined as the height of the bottom point of the evaporator above the bottom point of the condenser section. With adverse tilt, the returning condensate must be pumped uphill from the condenser to the evaporator. With the evaporator below the

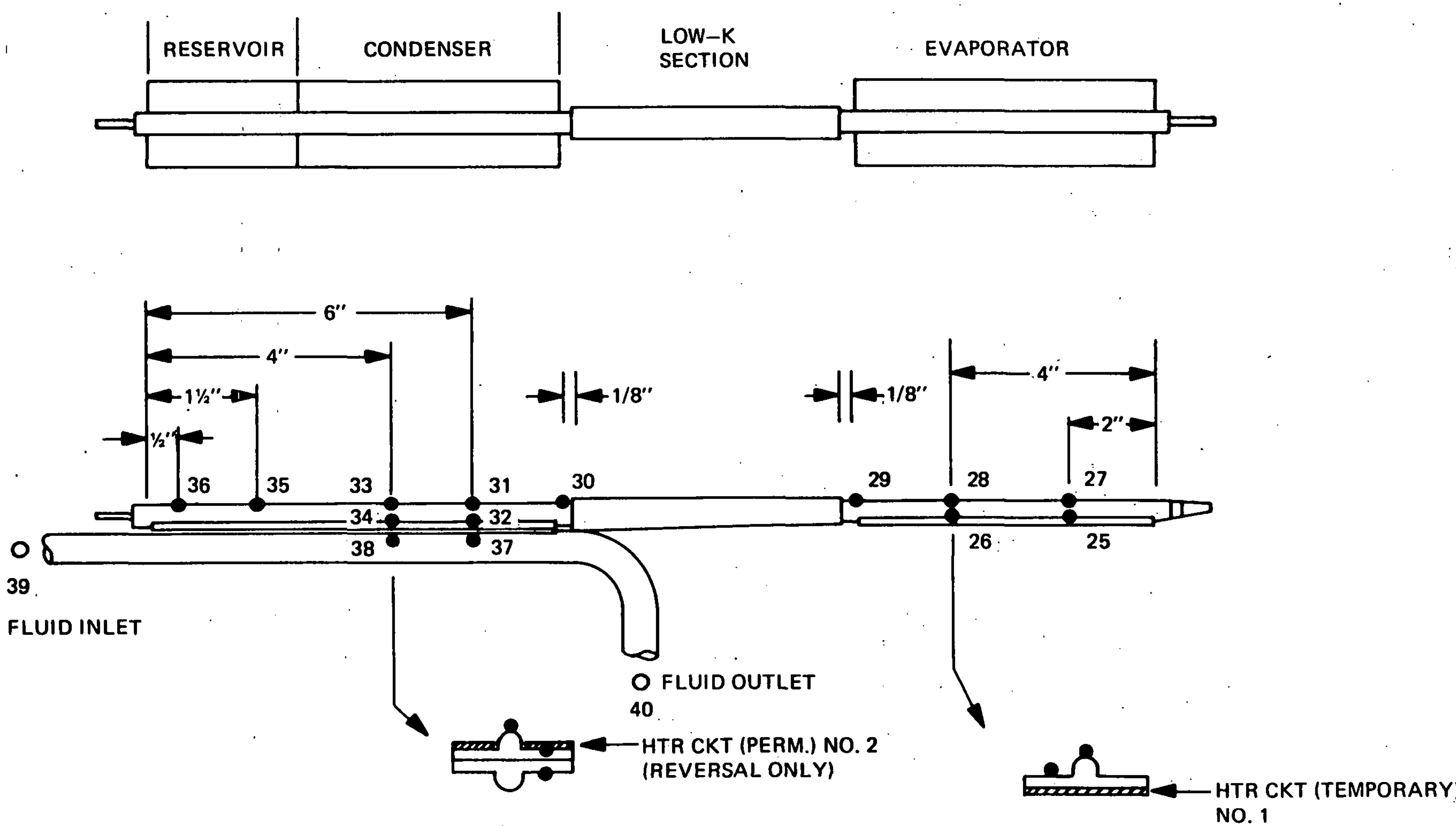


Fig. 3-13 Diode HP Bench Test Instrumentation Drawing

condenser ("favorable tilt") the condensate return is assisted by the force of gravity. After forward mode testing, heat was applied to the condenser flange to determine the reverse-mode temperature profile. Both forward- and reverse-mode bench tests were conducted before and after vibration testing to establish the effects of mission level vibration loads on thermal performance. Details of the vibration testing are given in Appendix A.

The first series of diode bench checks was terminated due to an undercharged condition - 14.5 grams of ammonia - was not enough to completely block the transport section during reverse mode operation. Operation in the forward mode was also below par as demonstrated by premature burnout ($\approx$ 33 watts) at moderate temperature (55°F). However, it was able to hold 51 watts at a vapor temperature of 109°F. Capacity at lower temperature ($\approx$ -10°F) was limited to about 20 watts.

The diode was recharged with 16.4 grams of ammonia and the tests repeated. The additional charge completely blocked the transport section during the reverse mode. Capacity during the normal operating mode was increased to about 50 watts for moderate to high temperature (55 to 110°F). However, at slightly higher loads, the pipe failed to function properly as witnessed by excessively high Δ Ts between the evaporator and condenser sections. It did not burnout in the conventional manner, with one of the evaporator thermocouples increasing in temperature at an alarming rate. Instead, the entire evaporator section increased in temperature and held at a higher level; the final evaporator temperature being a direct function of the heat load. Each increase in heat load brought a higher evaporator temperature and a greater Δ T between evaporator and condenser.

When these higher heat loads were applied, as step functions, the diode functioned as a proper HP for a short while. However, after a few minutes the evaporator section separated from the condenser and the excessively large Δ Ts were reestablished. This behavior is indicative of a non-wetting surface, therefore the charge was dumped and the HP flushed to wash out any impurities that might be present. After three ammonia flush charges, the pipe was recharged with 16.6 grams of ammonia and bench testing was resumed. There was no noticeable difference in forward mode performance from the previous test.

The bench test results for the last test series (see Fig. 3-14) show that a 40-watt capacity is achieved in the 55 to 105°F vapor temperature range with a flange-to-flange Δ T of less than 10°F. The lowest temperature (-10°F) test point shows a 13-watt capacity although a 20-watt capacity was achieved during earlier tests and can be expected. Figure 3-15 shows conductance as a function of vapor temperature and Fig. 3-16 shows the temperature profile through the diode during reverse mode operation. Complete blockage of the low-k transport section was established.

All diode testing was done with a charge valve on the condenser end of the pipe. Since the valve and its associated tubing can hold 2-3 grams of ammonia, it was assumed that the valve retained some charge at the lower temperatures, resulting in an undercharged condition in the working sections of the pipe. Performance degradation of an undercharged HP is especially pronounced at low temperatures because of the increased fluid density i.e., a greater mass of ammonia is required to completely fill the void within the artery at lower temperatures. The probable performance degradation due to the presence of the valve, coupled with acceptable performance at moderate to high temperatures led to the decision to continue through the development test cycle. The diode was pinched off, vibration tested, and rechecked.

Post-vibration thermal bench testing showed no noticeable performance degradation in either operating mode. (See Fig. 3-17.) Reasonable temperature drops were produced at moderate temperatures (55-110°F sink) for the 40 watt design load and somewhat poorer performance was noted at the coldest sink temperature.

Detailed data sheets for the diode thermal bench tests are contained in Appendix C.

3.2.2 Transport HP/PCM Canister

Figure 3-18 shows the instrumentation of the transport HP/PCM canister assembly during bench testing. It was instrumented with 24 copper/constantan thermocouples, 12 of which were within the PCM canister. Heat was applied to the evaporator section by heating the back of the simulated equipment baseplate; and was removed from the condenser by either a water spray bath (first test series) or a circulating-fluid cold plate that was clamped to it (second test series). Three inches of expanded polystyrene foam insulation surrounded the test specimen.

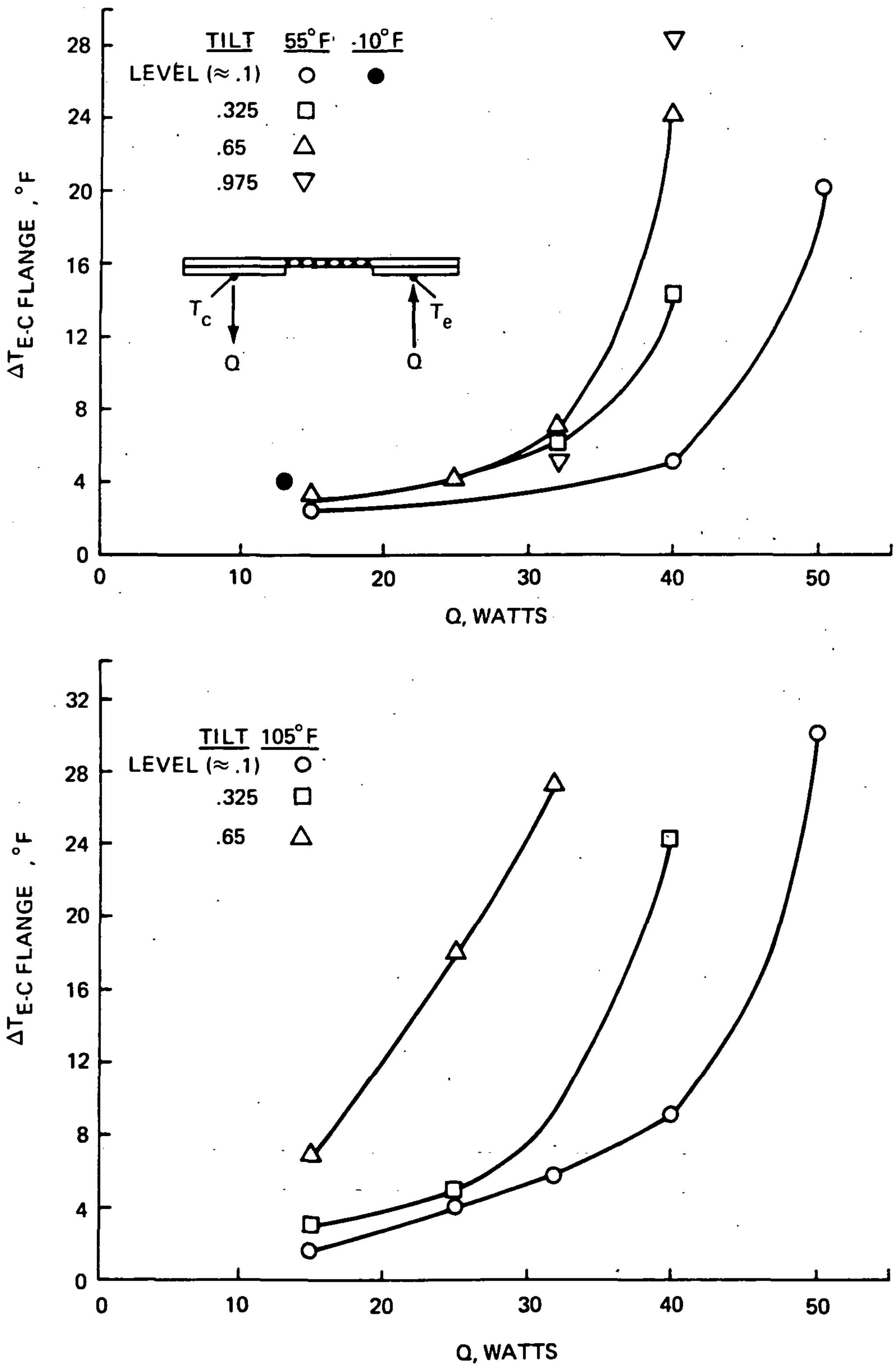


Fig. 3-14 Diode HP Bench Test Data, Flange-to-Flange ΔT vs Q

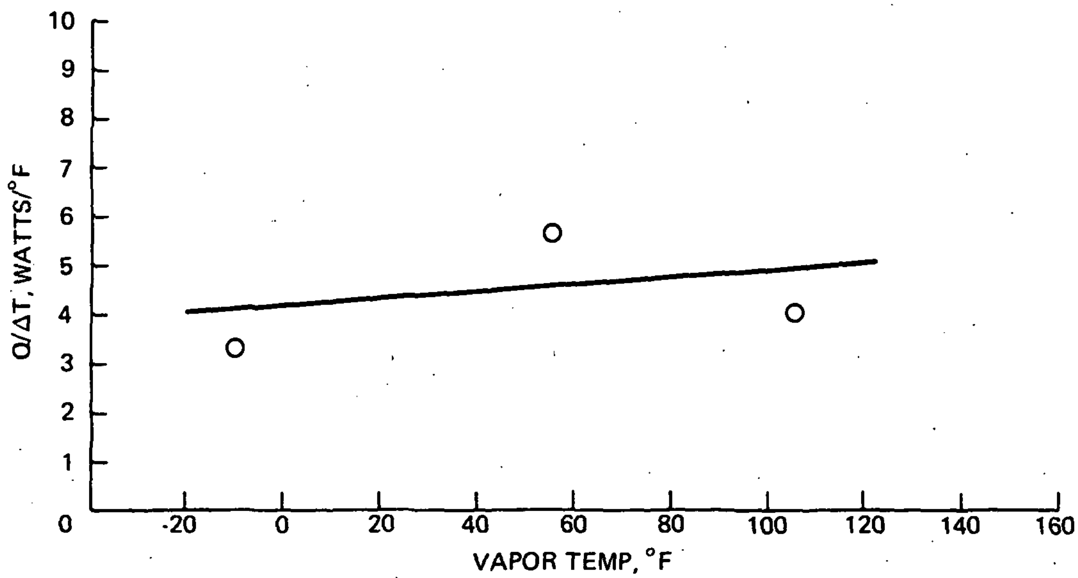


Fig. 3-15 Diode HP Bench Test Data, Forward Mode Conductance

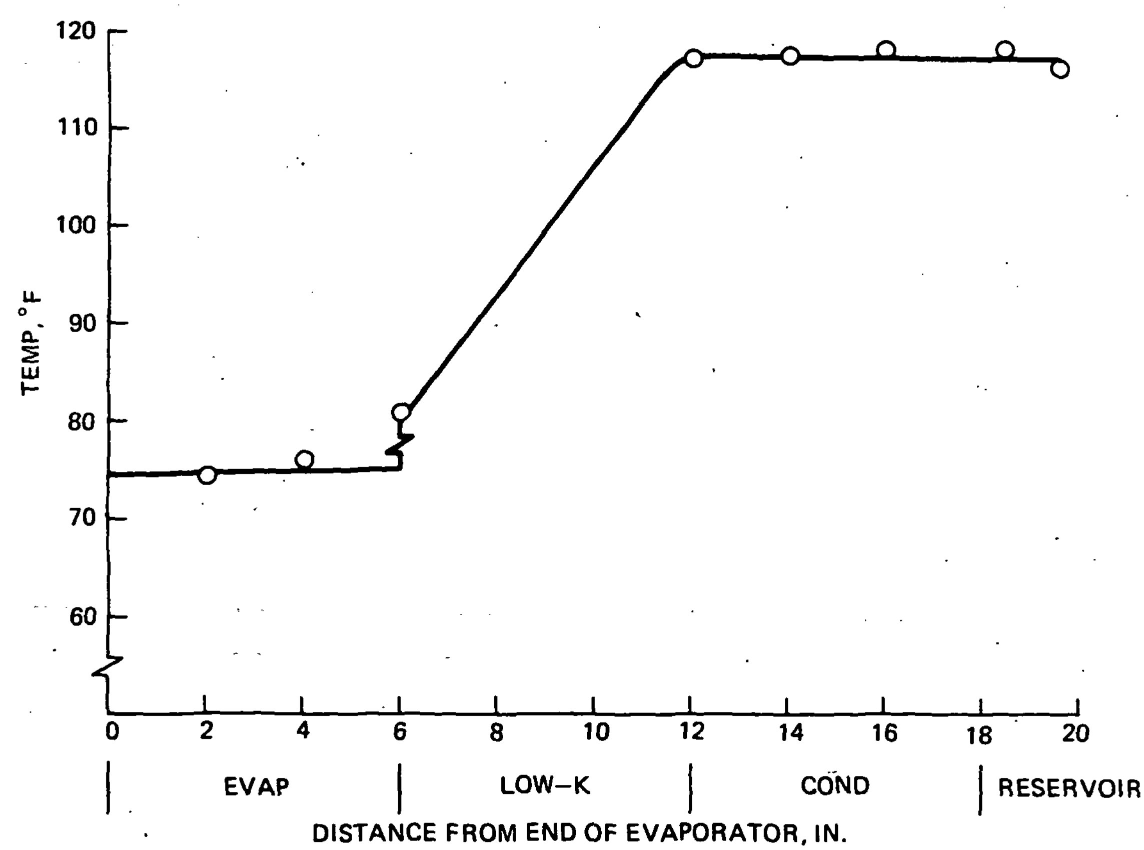


Fig. 3-16 Diode HP Bench Test Data, Reverse Mode Temperature Profile

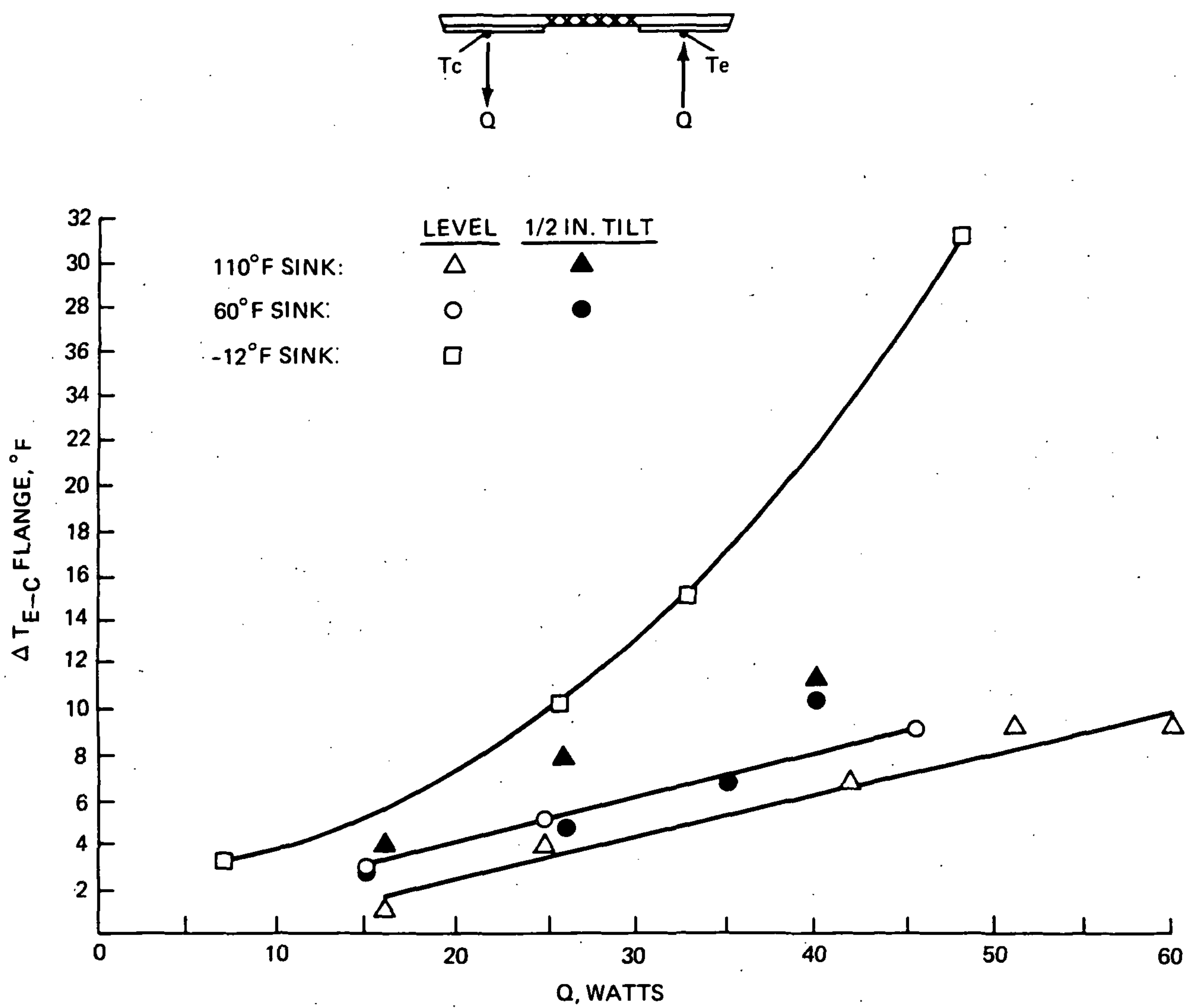


Fig. 3-17 Postvibration Performance, Diode HP

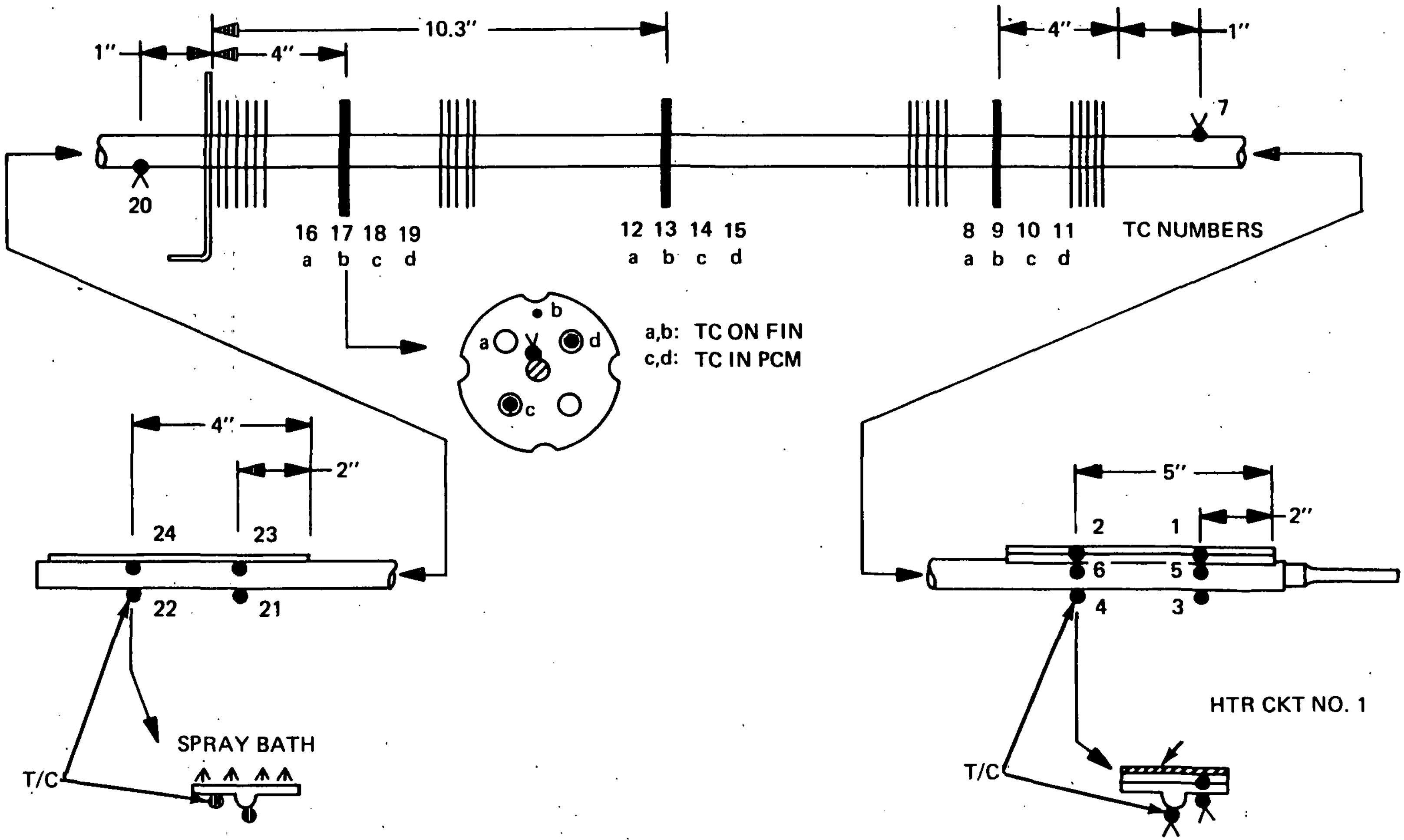


Fig. 3-18 Transport HP Bench Test Instrumentation

Bench tests were run with the system in a steady-state (straight-through) operating mode and a transient mode wherein the heat sink was the attached PCM canister. It was necessary to run two identical series of bench tests because of a faulty pinch-off after the first series was completed. This required the installation of a new pinch-off tube and another bake out and charge cycle for the heat pipe. At first the pipe was retested with only 30.5 grams of charge (2 grams less than the original charge) and it was impossible to get a capacity greater than 80 watts - an unacceptable value considering the 150-watt maximum obtained in the first series. Before the HP was recharged with 32.5 grams of ammonia, a leaky fitting on the charging station was replaced. The HP's performance with this final 32.5 gram charge (see Fig. 3-19) showed a marked improvement compared with the initial 32.5-gram charge. This difference might have been the result of non-condensible gases being admitted into the pipe during the initial 32.5 gram charging operation. At 1/4-in. tilt, maximum capacity was increased from 150 to 430 watts which is proof that the artery tunnel was not primed in the first case. The temperature differences between the evaporator and condenser sections were also improved due to the reduction in liquid film thickness at the walls when the central core of the artery fills with fluid. (See Fig. 3-20).

During the second series of tests, the condenser sink was changed from a shielded spray bath to a fluid cold plate clamped onto the flanged condenser section of the pipe. The cold plate method was an improvement in the component test setup since it represented the type of condenser interface used during system tests.

The transient series of tests proved very successful and demonstrated the 80 watt-hour heat capacity of the PCM canister. Figure 3-21 shows the transient test results when the pipe was loaded with 40 and then 80 watts. In each case, a distinctive melt region is detectable between 127° and 131°F. This is at variance with the 135°F melt temperature for myristic acid which is published in the literature. The slight difference should not adversely affect overall system performance. On the contrary, lower-than-design baseplate temperatures should be the result.

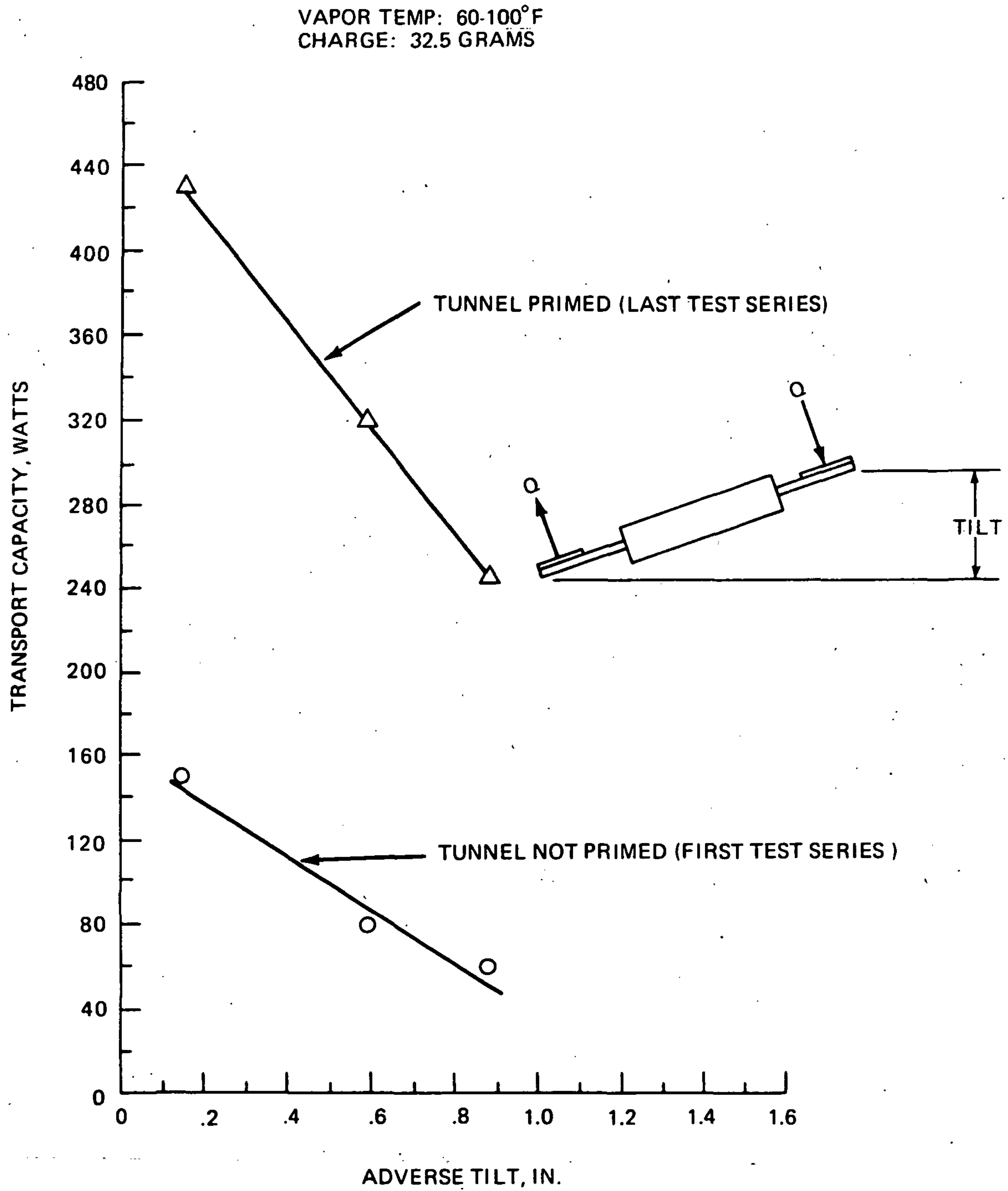


Fig. 3-19 Transport HP Bench Test Data, Q vs Tilt

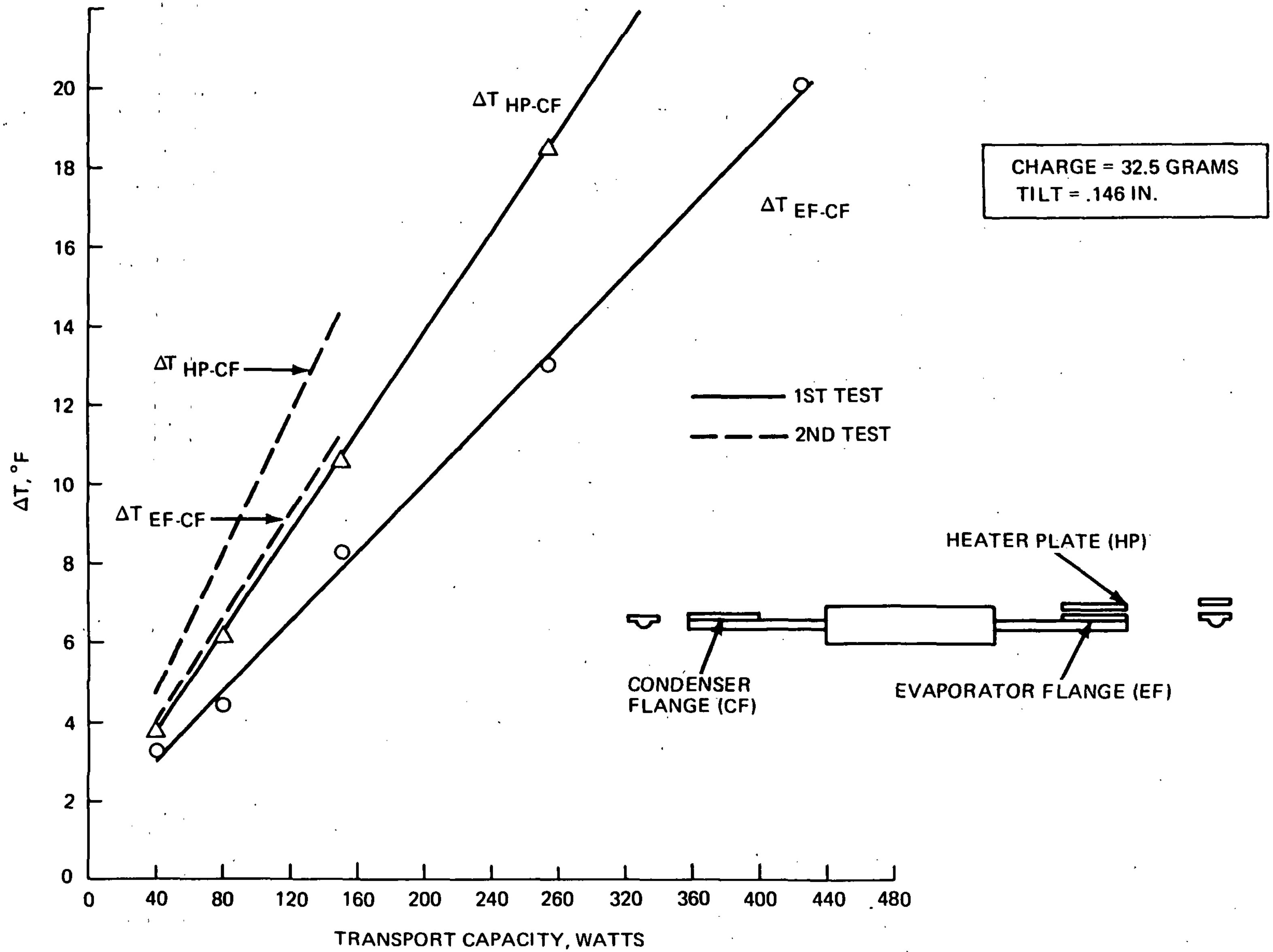


Fig. 3-20 Transport HP Bench Test Data, ΔT vs Q

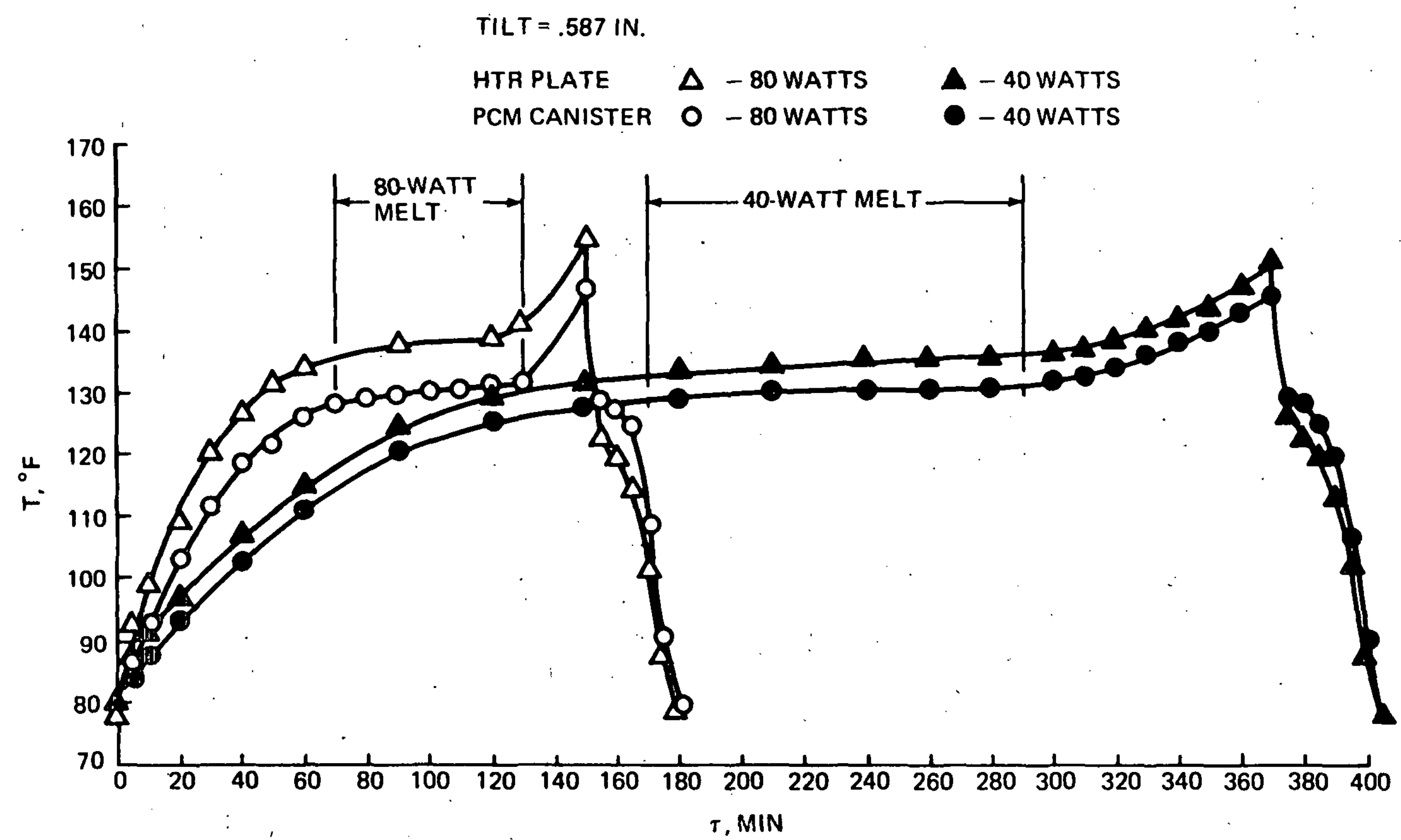


Fig. 3-21 Transient Performance, PCM Melting

The circumferential fins within the PCM canister proved highly efficient since temperature variations within the canister were less than 2°F during the time it was being loaded. The behavior of the canister during unloading to an 80°F sink (cold plate with 80°F circulating water) can be seen in Fig. 3-22. The portion of the canister farthest from the sink unloaded at a slightly slower rate than the portion closest to the sink but for all practical purposes, the canister can be considered to behave as a single lumped parameter. The entire cooldown period was less than 30 minutes.

Detailed data sheets for the transport HP thermal bench tests are contained in Appendix D.

3.3 SYSTEM TEST RESULTS

Figure 3-23 shows the setup and instrumentation of the modular heat sink for the system thermal tests. The same basic instrumentation from the component bench tests was used; a total of 40 copper/constantan thermocouples and two heater circuits, one circuit for the simulated equipment load and one for the reverse mode condition. The assembled system is shown in Fig. 3-24. During testing, the entire system was encased in 2 to 3 in. of expanded polystyrene insulation to minimize heat losses.

The steady state performance of the system was determined for incremental heat inputs up to 40 watts and varying sink temperatures between -40°F and 110°F. A more powerful refrigeration system was used during these tests in order to come closer to the -40°F lower limit than was possible during the bench tests. System test points were chosen to provide a performance map over the entire operating range in the normal mode. Transient performance (PCM melting) was obtained by raising the sink temperature to the 200°F level and maintaining the equipment heat load. Transient tests were run for both a static 1-g ground condition and a 3-g reflux condition using a centrifuge.

Table 3-1 summarizes the system tests that were run. Tests 1 through 10, 11, and 12 provide system steady state temperatures with simulated equipment heat loads of 5, 15, and 40 watts and simulated structural sink temperatures of -40°F (223.2°K), 30°F (272.0°K), 70°F (294.3°K), and 100°F (316.5°K). These test points were chosen

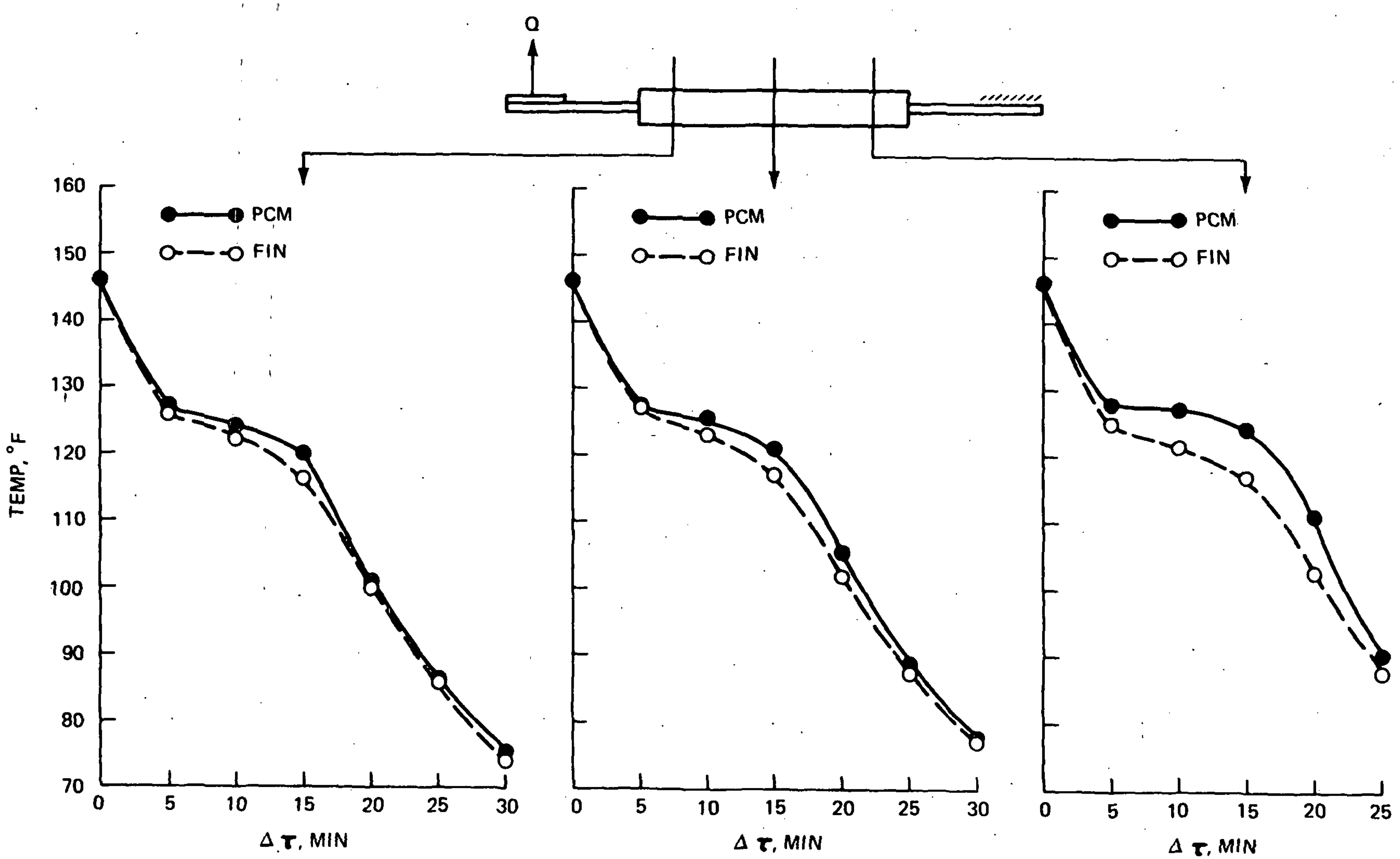


Fig. 3-22 PCM Cool Down Temperature History From 146°F, 80-Watt-Hours

FOLDOUT FRAME 1

FOLDOUT FRAME 2

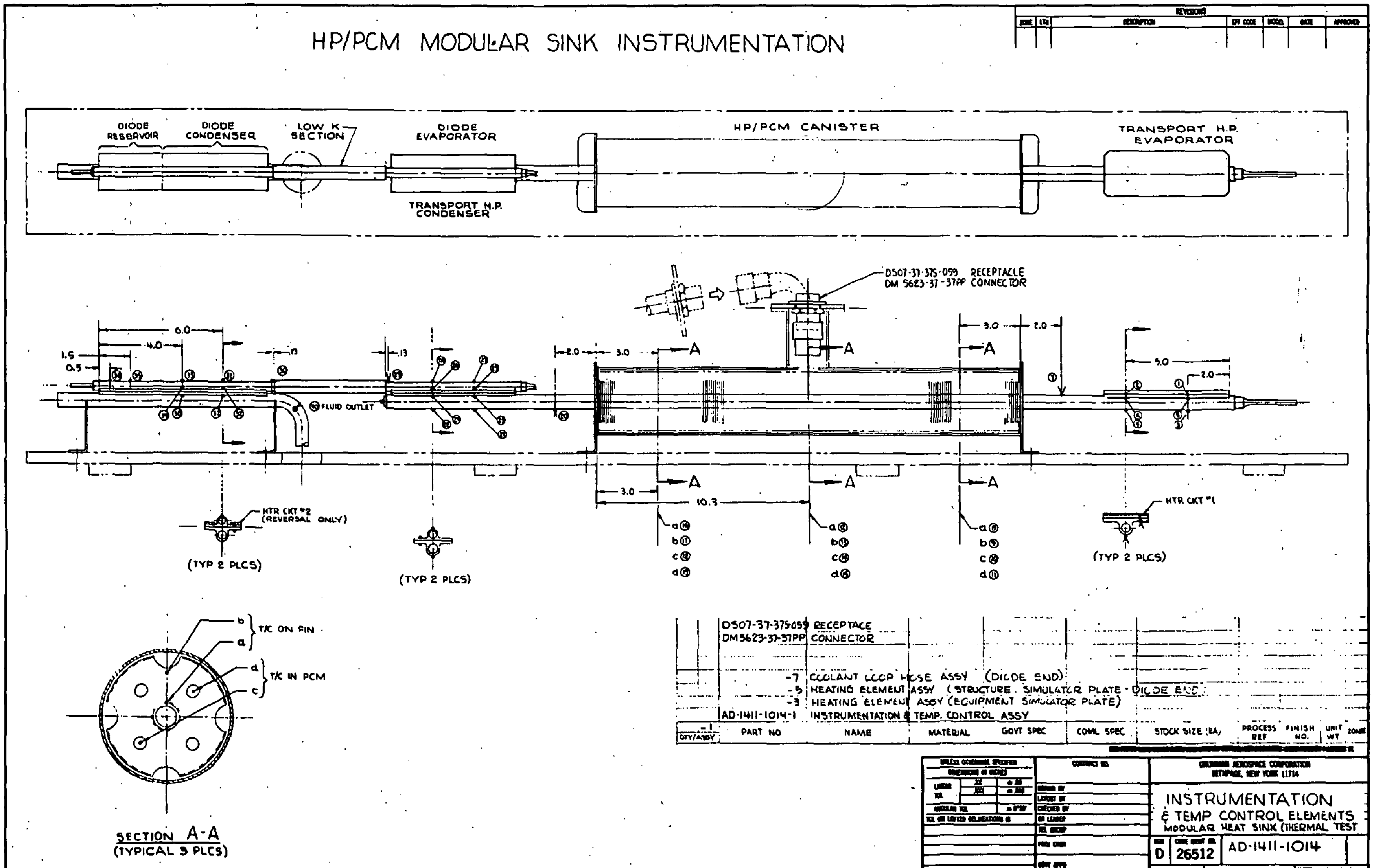


Fig. 3-23 Modular Heat Sink Instrumentation Drawing

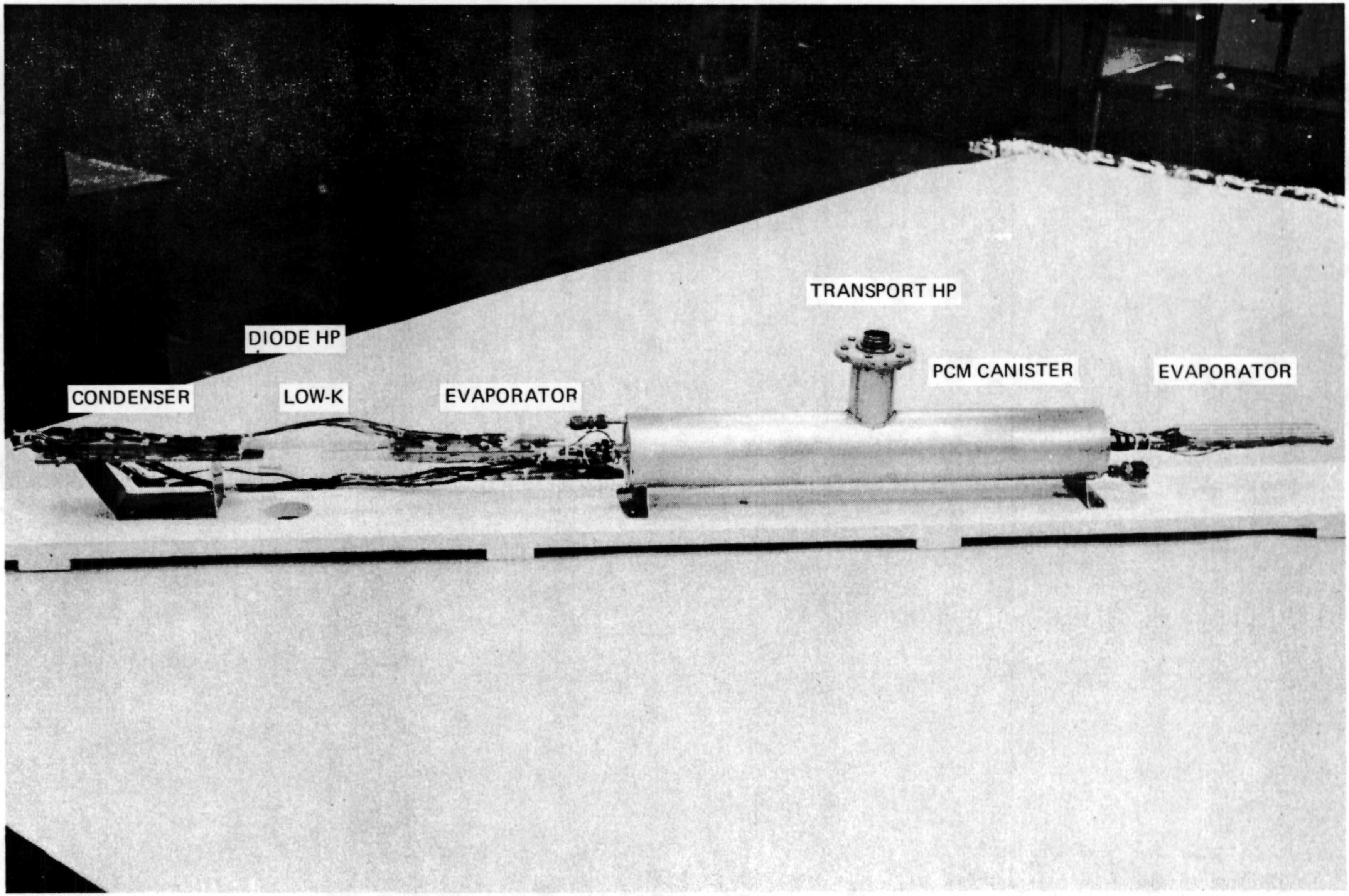


Fig. 3-24 Modular Heat Sink System

TABLE 3-1 MODULAR HEAT SINK SYSTEM TEST CONDITIONS

TEST NO.	EQUIPMENT Q, WATTS	SINK TEMP, °F (°K)	COMMENTS
1	5	-40 (223.2)	steady-state
2	15	-40 (233.2)	steady-state
3	40	-40 (223.2)	steady-state
4	5	30 (272.0)	steady-state
5	15	30 (272.0)	steady-state
6	40	30 (272.0)	steady-state
7	5	70 (294.3)	steady-state
8	15	70 (294.3)	steady-state
9	40	70 (294.3)	steady-state
10	5	110 (316.5)	steady-state
11	15	110 (316.5)	steady-state
12	40	110 (316.5)	steady-state
13	80	*	transient
14	5	110 (316.5)	steady-state, reflux
15	15	110 (316.5)	steady-state, reflux
16	40	110 (316.5)	steady-state, reflux
17	80	*	transient, reflux
18	80	**	transient, centrifuge

*From an initial temperature of 110°F (316.5°K), the sink temperature was rapidly raised to 207°F (370.4°K), and held at that level until the PCM was completely melted. At this point, the equipment power was cut off and the sink temperature lowered to 80°F (299.9°K) and held until the PCM has resolidified.

**Centrifuge test. Heat was applied to the diode condenser, shutting off the diode pipe, and an 80 watt load was input to the evaporator of the transport HP. Transients were recorded at inertial loads as high as 3g.

to provide a performance map of the system over its entire design operating range in the normal (PCM unmelted) mode. Sequence 13 tested the transient performance of the PCM. From an initial temperature of 110°F (316.5°K), the sink temperature is rapidly raised to 207°F (370.4°K) and held at this level until the PCM is completely melted. An 80-watt load is used to accelerate test time. The equipment power is then cutoff, and the sink temperature is lowered to 80°F (299.9°K) and held at this level until the PCM resolidified. Tests 14 through 17 repeated the thermal boundary conditions of tests 10 through 13, but with the system mounted vertically so that the transport pipe is operating as a reflux boiler. The assembly was then placed on a centrifuge and tested at a maximum inertial load of 3g to establish performance under entry-level inertial loads. Heat was applied to the diode condenser so that the diode shuts off, and 80 watts of thermal energy was applied to the evaporator section of the transport heat pipe.

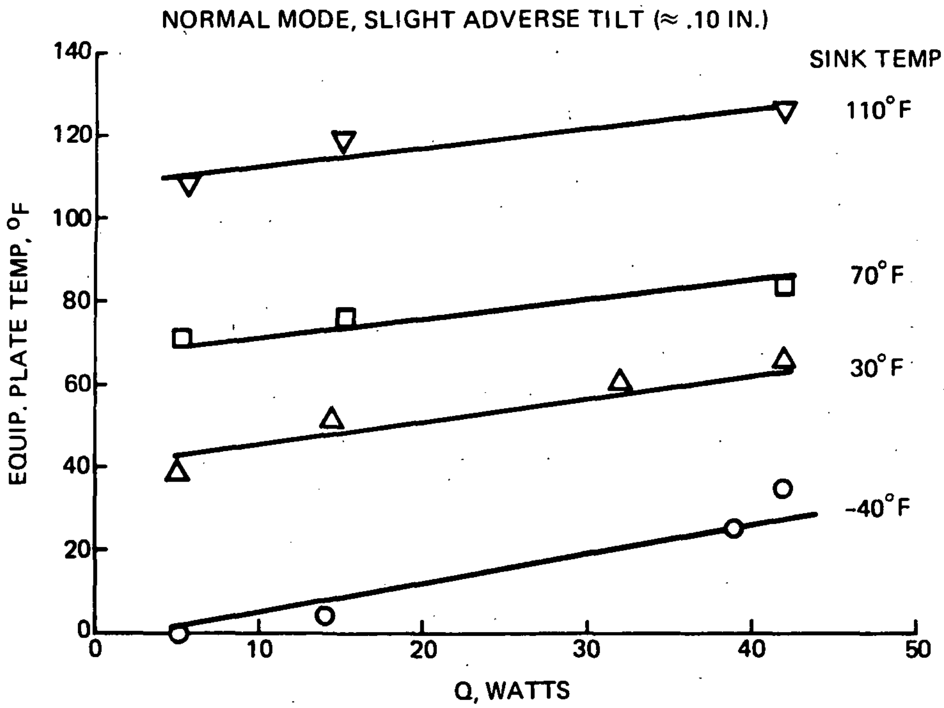
Pretest predictions of system performance were made using standard thermal modeling techniques. Table 3-2 contains these results and lists predicted temperatures throughout the system for the various steady state test conditions. The overall system conductance from equipment cold plate to diode condenser was estimated as 2.9 watts/°F. The predictions reflect the following nominal system parameters:

Parameter	Nominal Value
$h_{interface}$	1000 BTU/hr ft^2 °F
$h_{evaporator}$	2700 BTU/hr ft^2 °F
$h_{condenser}$	3500 BTU/hr ft^2 °F

System test results showed that the modular heat sink system met its overall performance requirements. It transmitted at least 40 watts over its -40 to 110°F operating range while holding the simulated equipment baseplate to less than 140°F. Figure 3-25 presents the normal mode test results for both the near-level condition (slight adverse tilt) and the reflux boiler condition. It gives baseplate temperature as a function of heat load for various sink temperatures.

TABLE 3-2 MODULAR HEAT SINK PRETEST PREDICTIONS

TEST NO.	Q, WATTS	T_{SINK}	$T_{DIODE\ COND}$		$T_{DIODE\ EVAP}$		$T_{TRANS\ COND}$		$T_{PCM\ CANISTER}$		$T_{TRANS\ EVAP}$		$T_{EQUIP\ COLD\ PLATE}$	
		°F	°F	°K	°F	°K	°F	°K	°F	°K	°F	°K	°F	°K
1	5	-40	-39.1	233.7	-38.7	233.9	-38.1	234.2	-38.0	234.3	-37.9	234.3	-37.4	234.6
2	15	-40	-37.2	234.7	-36.0	235.4	-34.4	236.3	-34.1	236.4	-33.7	236.7	-32.1	237.6
3	40	-40	-32.5	237.3	-29.4	271.7	-25.2	241.4	-24.3	241.9	-23.3	242.4	-18.9	244.9
4	5	30	30.9	272.6	31.3	272.8	31.9	273.1	32.0	273.2	32.1	273.2	32.6	273.5
5	15	30	32.8	273.6	34.0	274.3	35.6	275.2	35.9	275.3	36.3	275.6	37.9	267.4
6	40	30	37.5	276.2	40.6	277.9	44.8	280.3	45.7	280.8	46.7	281.3	51.1	283.8
7	5	70	70.9	294.8	71.3	295.0	71.9	295.3	72.0	295.4	72.1	295.4	72.6	295.7
8	15	70	72.8	295.8	74.0	296.5	75.6	297.4	75.9	297.6	76.3	297.8	77.9	298.7
9	40	70	77.5	298.4	80.6	300.2	84.8	302.5	85.7	303.0	86.7	303.6	91.1	306.0
10	5	110	110.9	317.0	111.3	317.2	111.9	317.6	112.0	317.6	112.1	317.7	112.6	317.9
11	15	110	112.8	318.1	114.0	318.7	115.6	319.6	115.9	319.8	116.3	320.0	117.9	320.9
12	40	110	117.5	320.7	120.6	322.4	124.8	324.7	125.7	325.2	126.7	325.8	131.1	328.2



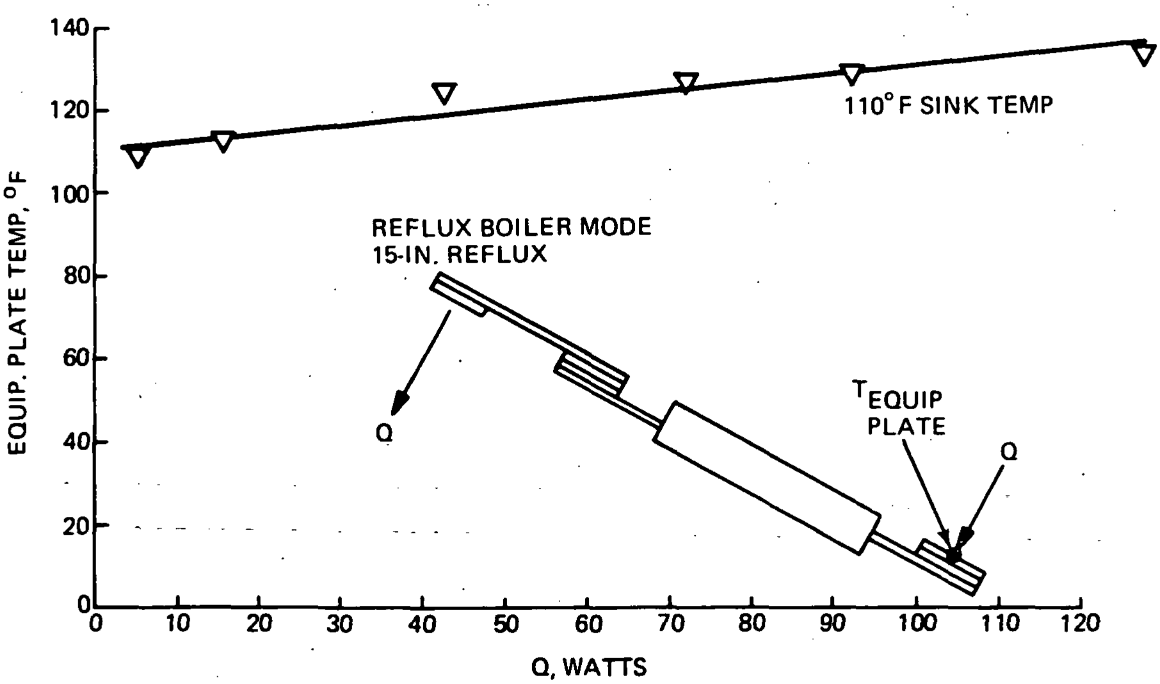


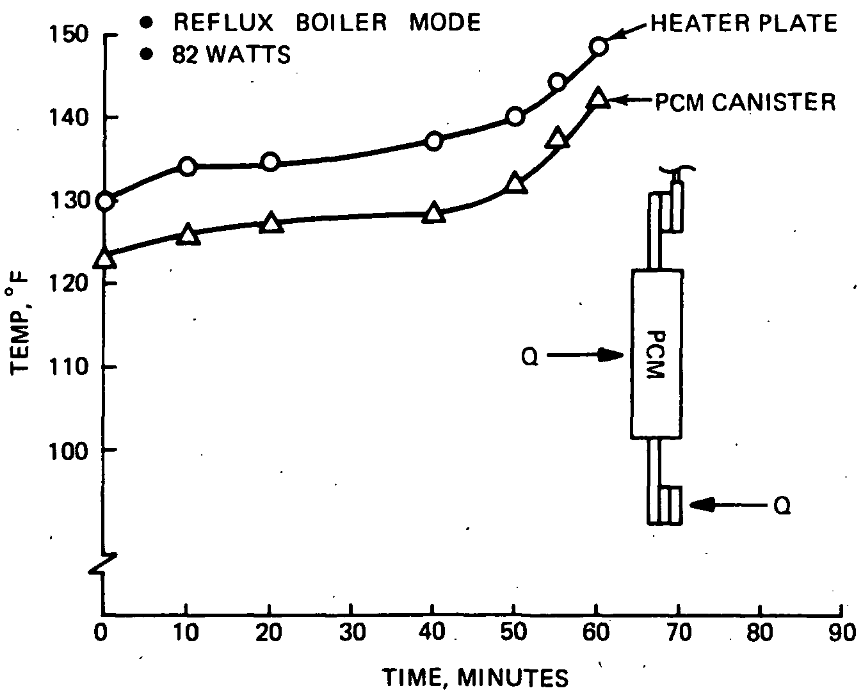
Fig. 3-25 Modular Heat Sink System Test Results, Normal Mode

Transient performance during the simulated entry condition (sink temperature $\approx$200°F) is given in Fig. 3-26. The diode shut off as planned and successfully decoupled the transport HP from the 200°F sink. Figure 3-27 shows the temperature/time history for the equipment heater plate and PCM canister during this simulated entry. Heater plate temperature was kept below 140°F for 50 minutes with an 82-watt heat load. This exceeded the required 40-minute entry time and 40-watt dissipation. As can be seen, performance is the same for both the reflux boiler mode and the near-level mode.

Detailed data sheets for the modular heat sink system tests are contained in Appendix E.

After the 1-g system tests, the modular heat sink was successfully operated in the reflux mode while being subjected to a nominal 3-g inertial environment. The system was mounted colinearly with the radius arm of a 19-foot centrifuge. The diode was positioned nearest the center of rotation and the evaporator of the transport HP was fixed at the outermost point on the arm. Thus, the g-vector was directed outward from the center of rotation toward the evaporator of the transport pipe. This placed the system in a reflux operating mode. Because the size of the test specimen (modular heat sink) was large compared with the centrifuge arm, a non-uniform g-vector was impressed across it. The highest g-levels were at the outside radius (transport HP evaporator) and the lowest at the inside radius (diode HP reservoir). During the test, the actual gradient between these locations was from 3.15 g to 2.35 g while the arm rotated at 22 rpm.

An electrical noise problem was experienced during system testing. About 6 millivolts of noise was generated by the slip rings located on the hub of the centrifuge while the normal copper/constantan thermocouple output was on the order of 1 to 2 millivolts. To overcome this problem, a 4-channel amplifier was used, but a problem in one of its channels limited the number of thermocouples (TCs) that could be monitored to three: TC 1 – on the simulated equipment heater plate, TC 14 – in the PCM canister, and TC 32 – at the condenser flange of the diode. Accuracy for the thermocouple readout is estimated at no better than ±5°F due to excessive noise in the system.



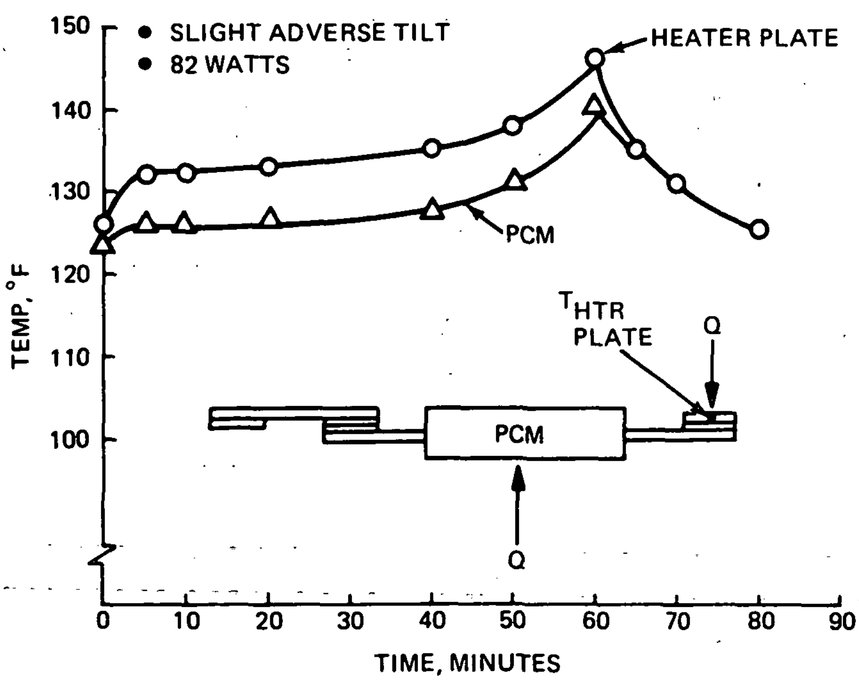


Fig. 3-26 Modular Heat Sink System Test Results, Transient Mode – PCM Melting

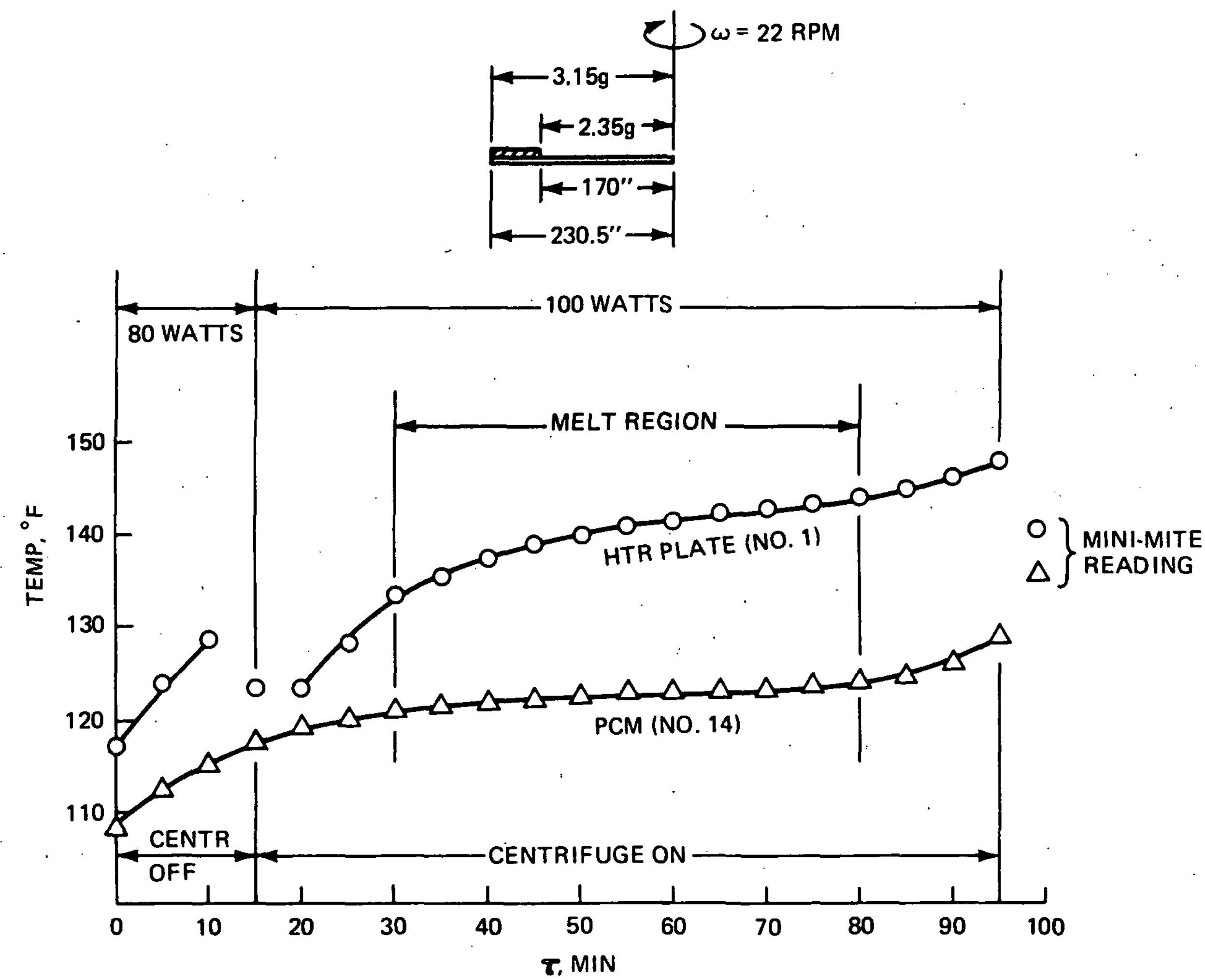


Fig. 3-27 Modular Heat Sink Centrifuge Test Results

The entire modular heat sink system was insulated with 1-in. thick Armaflex foam rubber to minimize heat losses. This insulation was much less effective than the 3-in. of expanded polystyrene that was used for the bulk of the system testing in the laboratory. Consequently, it was necessary to increase the heater power input from 80 watts to 100 watts to offset the additional heat losses to the environment. System heat leaks were further aggravated by the fact that the outside surface was moving at approximately 38 ft/sec. This increased the convective coupling to the ambient. A more elaborate insulation scheme could not be justified since it would add cost and delay the schedule without really adding anything of significance to the test. The test objective was to establish that the system would operate under a 3-g environment and that was done with the system described.

Test results are presented in Fig. 3-27 which shows the temperatures of the PCM and the heater plate (simulated equipment) as a function of time. The appearance of a definite melt region in both curves is evidence that the modular heat sink was operating properly. Melting of the PCM took place over an approximate 50 minute period. The melt temperature range of the PCM as indicated by the curve is 120 to 124°F as compared with the 127 to 131°F range that was obtained during the 1-g system testing. The difference is attributed to the poorer accuracy inherent in the centrifuge test instrumentation.

Section 4

HEAT PIPE RADIATING PANEL

The HP radiating panel represents a simple method for utilizing available fluid waste heat sources to supply energy for on-orbit thermal control of shuttle compartments. It is part of an integrated thermal control system concept which couples areas that have excess thermal energy and require cooling, with those areas that need additional heat to maintain acceptable temperatures. In this case, the waste heat source is hydraulic fluid and the radiating panel is typical of one that could be used to maintain a -20°F minimum temperature for the main landing gear compartment.

As illustrated in Fig. 4-1, the panel consists of a 4 x 4 ft radiating fin assembly containing six L-shaped ammonia HPs. The pipes also use a spiral artery wicking system to insure self-priming and valid ground test results. The condenser section of each HP (long leg of L) is adhesively bonded to the radiating fin; the evaporator section (short leg) is mechanically clamped to the OD of a stainless steel hydraulic line. This type of system, while not the most thermally efficient, is a highly maintainable one that has minimum impact on the hydraulics subsystem since it does not require any internal or external fluid line modifications.

Heat is transferred from the hydraulic fluid line, through the mechanical interface and into the evaporator sections of the panel feeder HPs. It is then distributed along the length of the condenser sections by HP action and conducted to the radiating fin from where it is radiated to the compartment interior.

4.1 DESIGN DETAILS

4.1.1 Requirements

The following design requirements for the HP radiating panel are based on those of the main landing gear compartment but are generally applicable to any shuttle compartment.

Environment

- -40°F to 0°F

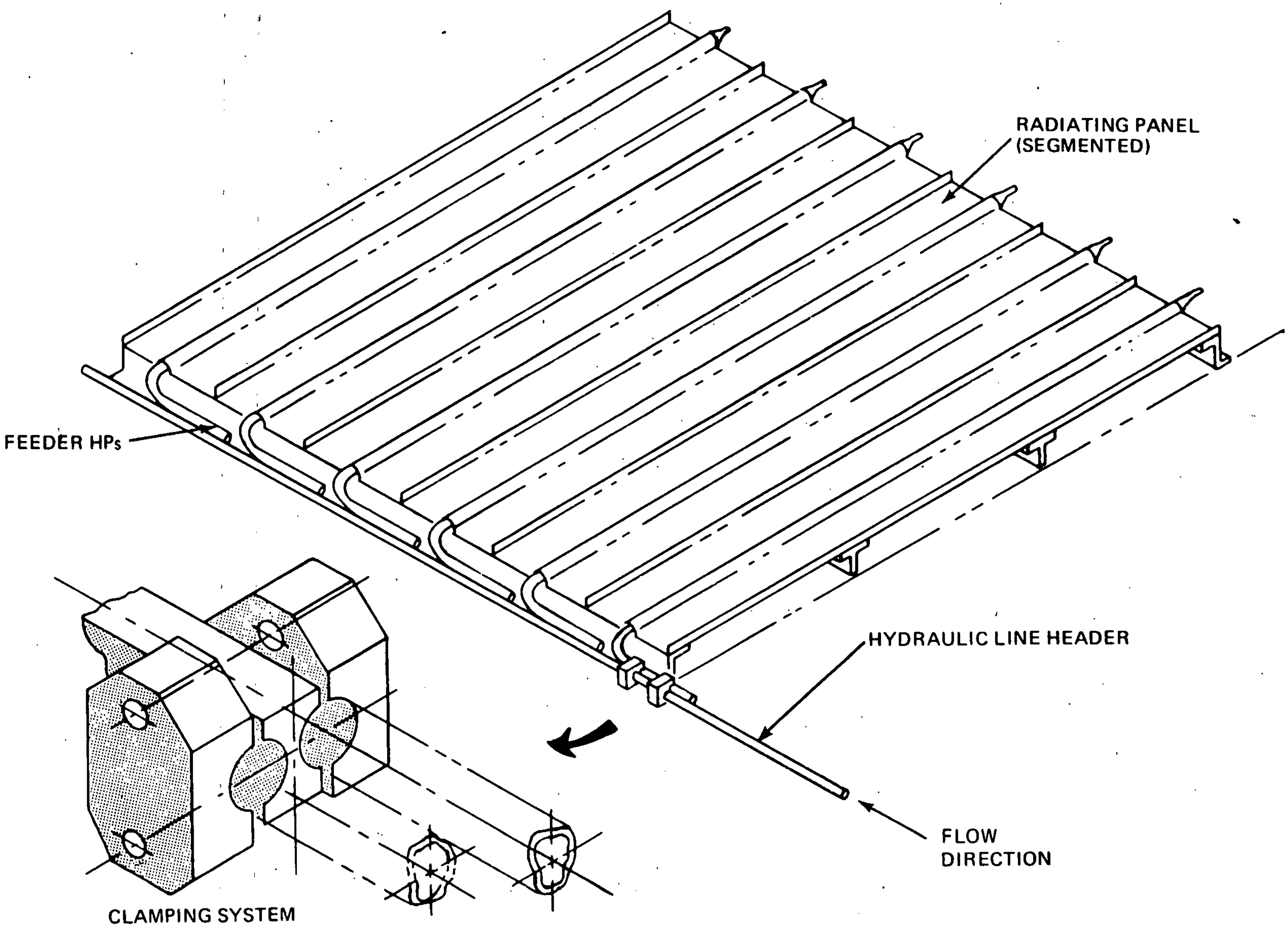


Fig. 4-1 Compartment HP Radiating Panel

Fluid Heat Source

- MIL-H-5606 hydraulic fluid
- 30°F to 90°F inlet
- .40 to 1.2 GPM flow rate

Radiating Fin

- 4 ft x 4 ft
- 6 panel feeder HPs
- 1.25 watt/ft^2 net heat rejection for .40 GPM, 90°F inlet, and -20°F environment

4.1.2 Feeder Heat Pipes

Figure 4-2 shows the overall configuration and design details for a panel feeder HP and its fin subassembly. The pipe uses a standard spiral artery/tunnel wick design with ammonia as the working fluid. Artery feeder pipes were selected over the simpler longitudinally grooved pipes to make the panel less sensitive to the effects of gravity and thus facilitate ground testing. Artery pipes are easily primed in 1-g and maintain their performance characteristics at adverse tilt.

A summary of the design details follows:

Envelope

- Material = Aluminum 6061-T6
- Grooves: circumferential, 150/in.
- Working fluid = ammonia (charge = 44 grams)

	Evaporator	Transport	Condenser
• ID, in.	.430	.430	.430
• OD, in.	.500	.500	.500
• Length, in.	6	3	48

Wick

- Material = 100/100 mesh stainless steel screen
- Artery/Retainer OD = .312 in.
- Tunnel Core Dia. = .094 in.
- Spiral Gap = .010 in.
- Retainer legs = 3

FOLDOUT FRAME 1

FOLDOUT FRAME 2

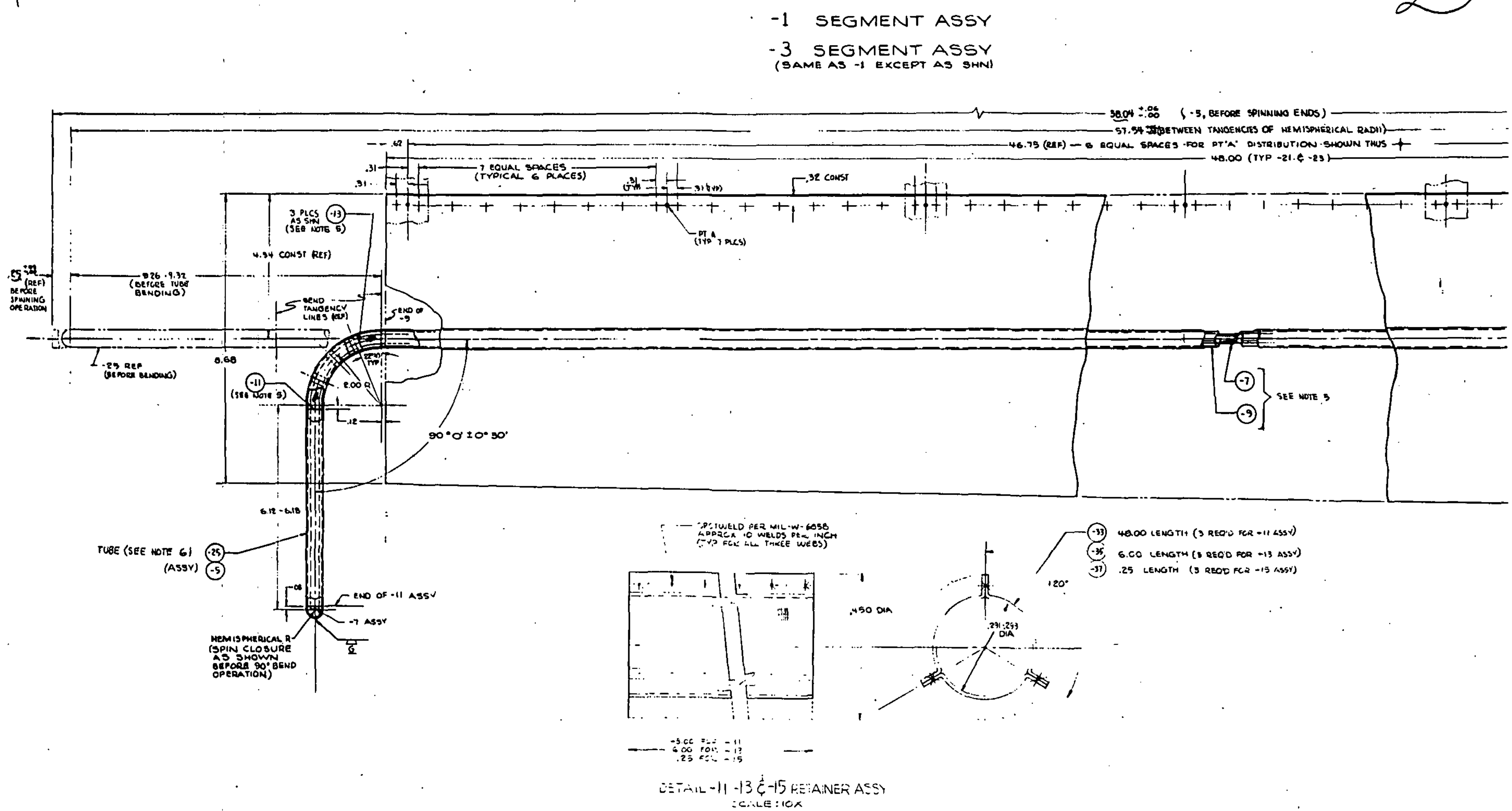
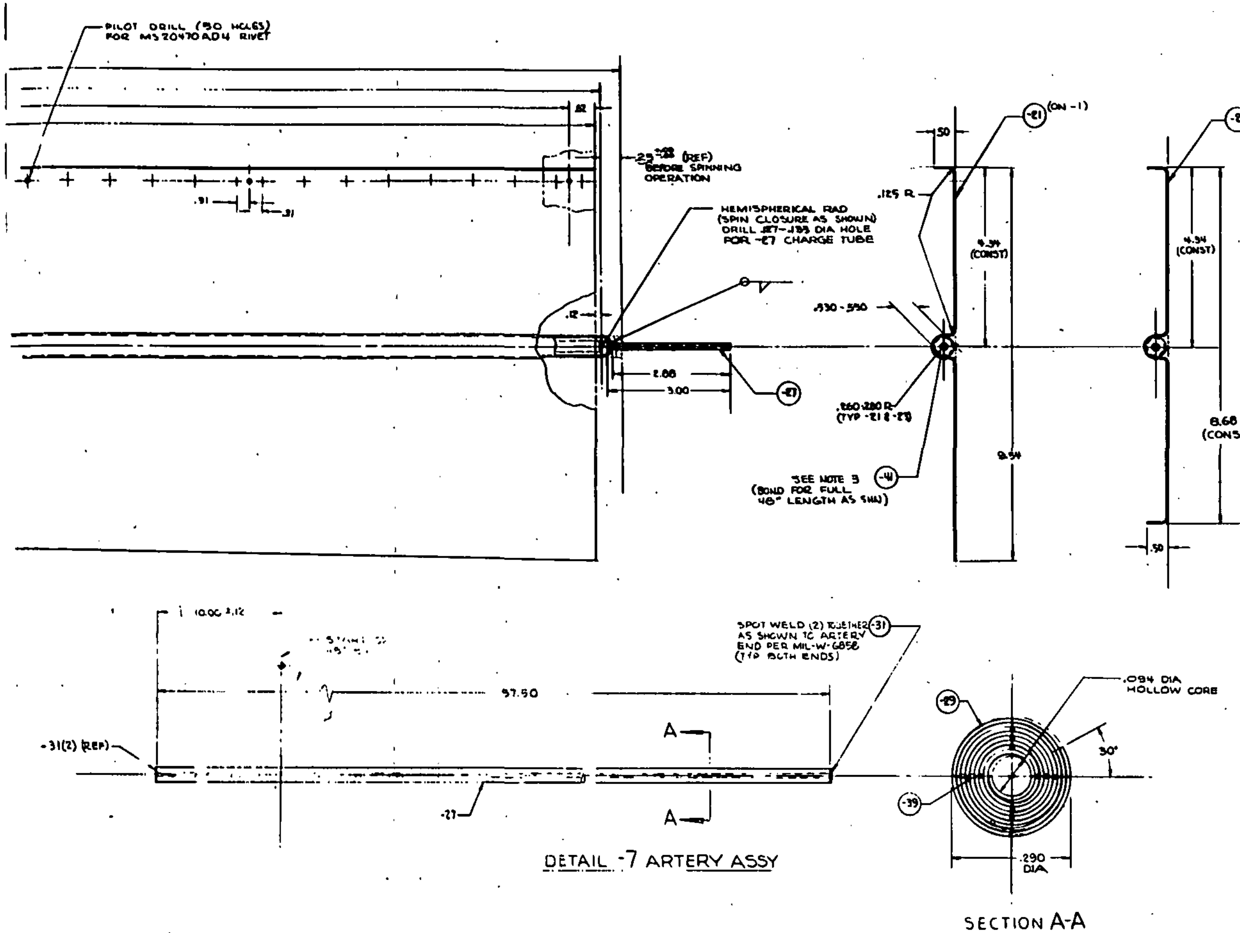


Fig. 4-2 Panel Segment and Feeder HP Drawing (Sheet 1 of 2)

FOLDOUT FRAME 1



FOLDOUT FRAME 2

NOTES (UNLESS OTHERWISE NOTED)

1- ALL AL ALY WELDING SHALL BE ACCORDANCE WITH MIL-W-8604 USING FILLER WIRE ALLOY 5183, 5356 OR 5556.

2- DESIGN CRITERIA FOR FEEDER HEAT PIPE
   - MAX OPERATING PRESSURE - 375 PSI
   - PROOF PRESSURE 575 PSI
   - BURST PRESSURE 750 PSI

3- APPLICATION OF -41 (NARMCO 7343/7139 SHALL BE IN ACCORDANCE WITH GSS-22404 TYPE I. PRE-BOND TREATMENT OF BONDING SURFACES SHALL BE IN ACCORDANCE WITH GSS-7022

4- -5 IS TO BE FULLY COMPLETED PRIOR TO THIS BENDING OPERATION

5- TACK WELD PER MIL-W-6858, -9, -11 & -13(3) RETAINER ASSEMBLIES ONTO -7 ARTERY ASSY IN THE RESPECTIVE POSITIONS SHOWN. INSTAL THIS RETAINER/ARTERY ASSY WITHIN -25 (BEFORE BENDING) BY PULL THRU METHOD DEVELOPED IN LAB

6- INSIDE DIA OF -25 SHALL BE THREADED (FULL LENGTH) 144 TO 160 THRDS/INCH. DEPTH OF THRD .005-.007

QTY REQD PER ASSY (-13, -11, -9, -7, -5, -3, -1)	PART NO	NAME	MATERIAL	GOVT SPEC	COML SPEC	STOCK SIZE (EA)	PROCESS (REF)	FINISH NO	UNIT WT	ZONE
AR AR	-41	ADHESIVE	NARMCO 7343/7139 (SEE NOTE 3)							
AR	-39	SPACER ROD	304 S.STL	RR-W-360		.010 WIRE DIA x A.R.				
3	-37	RETAINER WEB				100 MESH x .0045 W/D				
3	-35	RETAINER WEB								
3	-33	RETAINER WEB								
4	-31	DISK (ARTERY END)								
1	-29	ARTERY WEB	304 S.STL	RR-W-360		100 MESH x .0045 W/D				
1	-27	CHARGE TUBE	AL ALY 5052-O	QQ-W-700/4		.125 D x .035 WALL x 4.0				
1	-25	TUBE (FEEDER)	AL ALY 6061-T6			.500 D x .035 WALL x 60.0				
1	-23	PANEL	AL ALY 6061-T4 SH	QQ-A-250/4		.020 x 12.0 x 49.0				
1	-21	PANEL	AL ALY 6061-T4 SH	QQ-A-250/4		.020 x 12.0 x 49.0				
3	-13	RETAINER ASSY (TRANSPORT) — SEE NOTE 5								
1	-11	RETAINER ASSY (EVAPORATOR) — SEE NOTE 5								
1	-9	RETAINER ASSY (CONDENSER) — SEE NOTE 5								
1	-7	ARTERY ASSY — SEE NOTE 5								
1 1	-5	FEEDER HEAT PIPE ASSY								
	-3	SEGMENT ASSY (SEE N/A BLOCK)								
	AD-1411-1021-1	SEGMENT ASSY (SEE N/A BLOCK)								

PART NO	NEXT ASSY	MODULE OR SUB MODULE	
-3	AD1411-1020	1	
-1	AD1411-1020	5	

PART NO AD1411-1021

NAS 9-12801

PANEL SEGMENT & FEEDER HEAT PIPES THERMAL TEST

J 26512 AD-1411-1021

Fig. 4-2 Panel Segment and Feeder HP Drawing (Sheet 2 of 2)

The last 10 in. of the artery, at the evaporator end, are made from biased cut screen. This allows the artery to bend without kinks when the feeder pipe is formed into its L-shape. The ends of the pipe envelope are formed into hemispherical caps to preclude interference at the mating surfaces (evaporator to fluid line saddle) that might result from the end closure welding process.

Figure 4-3 shows the evaporator, transport and condenser sections in a bent configuration. The retainer assembly, which supports the artery in the condenser and evaporator sections is shown in Fig. 4-4.

The fin subassembly incorporates a cylindrical channel that forms a cradle for the condenser section of the feeder pipe. The pipe is attached to the subassembly by a polyurethane bonding agent that permits a strong, yet flexible bond. The temperature drop across the interface is kept small by the thin .010 to .015-in. bondline and the relatively large heat transfer area that is available.

The theoretical capacity of the feeder HP is well above its requirement for this particular application. Thus, the panel can be tested at much higher load levels if desired. Figure 4-5 illustrates this by giving capacity as a function of tilt for vapor temperatures of 0°F and 60°F.

The theoretical 100% fill charge was calculated for an operating vapor temperature of 0°F — the approximate mid-range value during the system tests. At higher vapor temperatures, such as those encountered during the bench tests, the ammonia volume increases and results in a partially blocked condenser. For example, at a vapor temperature of 90°F, the blocked length is calculated to be 7.4 in., or about 15% of the 48-in. condenser.

4.1.3 Panel

The actual HP radiating panel is made by riveting together six of the feeder pipe/fin subassemblies. Details of the assembled panel are given in Fig. 4-6. The evaporator sections of the feeder pipes are joined to the stainless steel hydraulic fluid line by simple saddle blocks. All of the clamped interfaces are coated with thermal grease (DC 340) to increase the interface conductance. This is especially important for the evaporator sections where heat transfer area is at a premium.

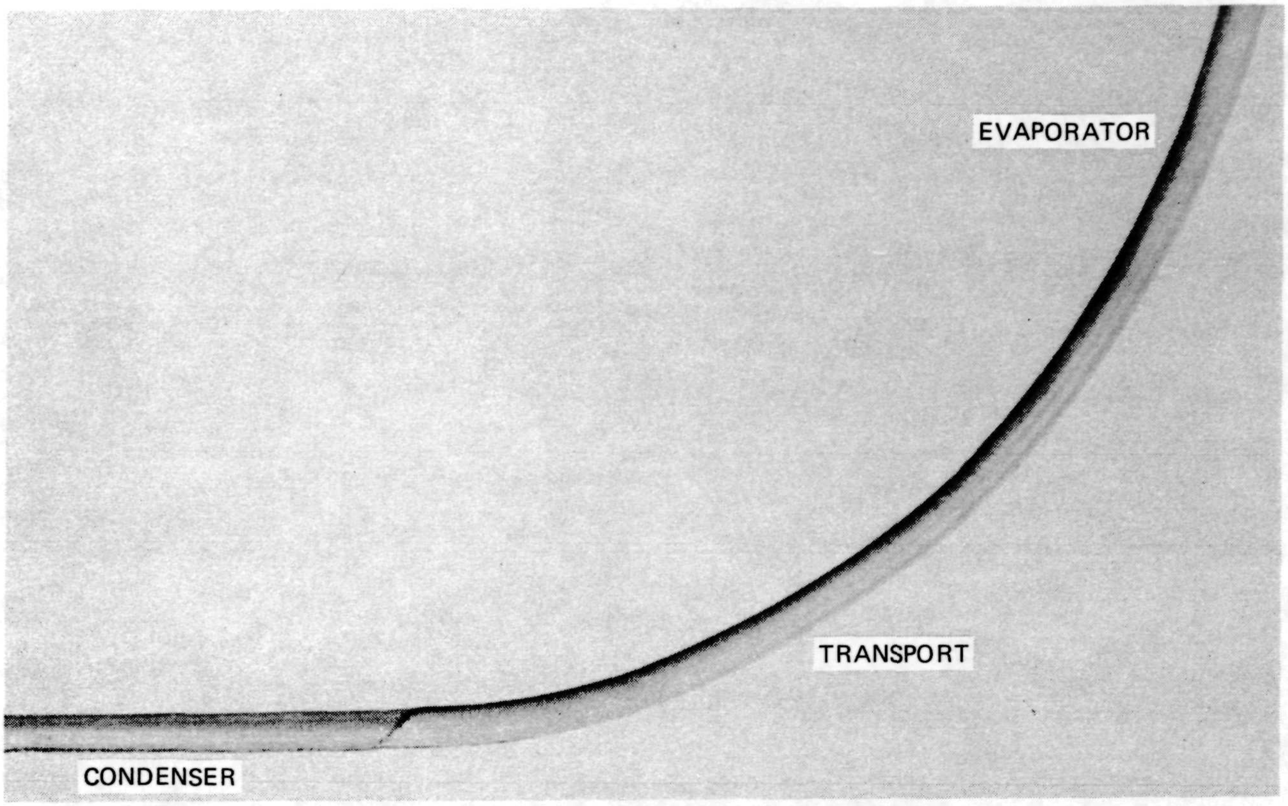


Fig. 4-3 Feeder HP Artery

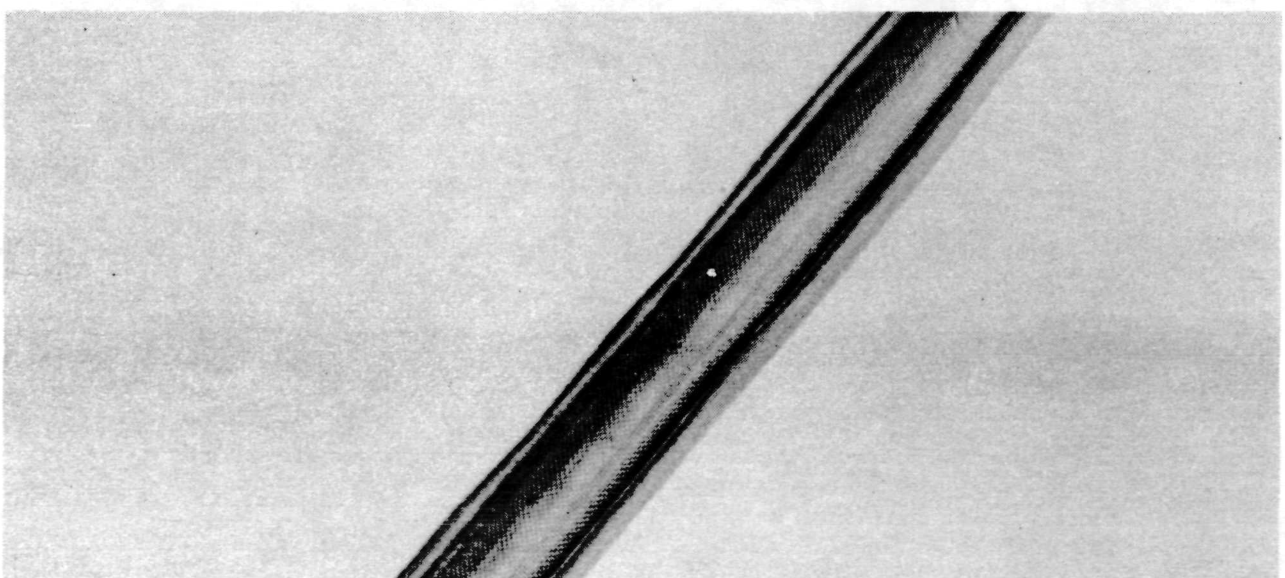


Fig. 4-4 Feeder HP Retainer

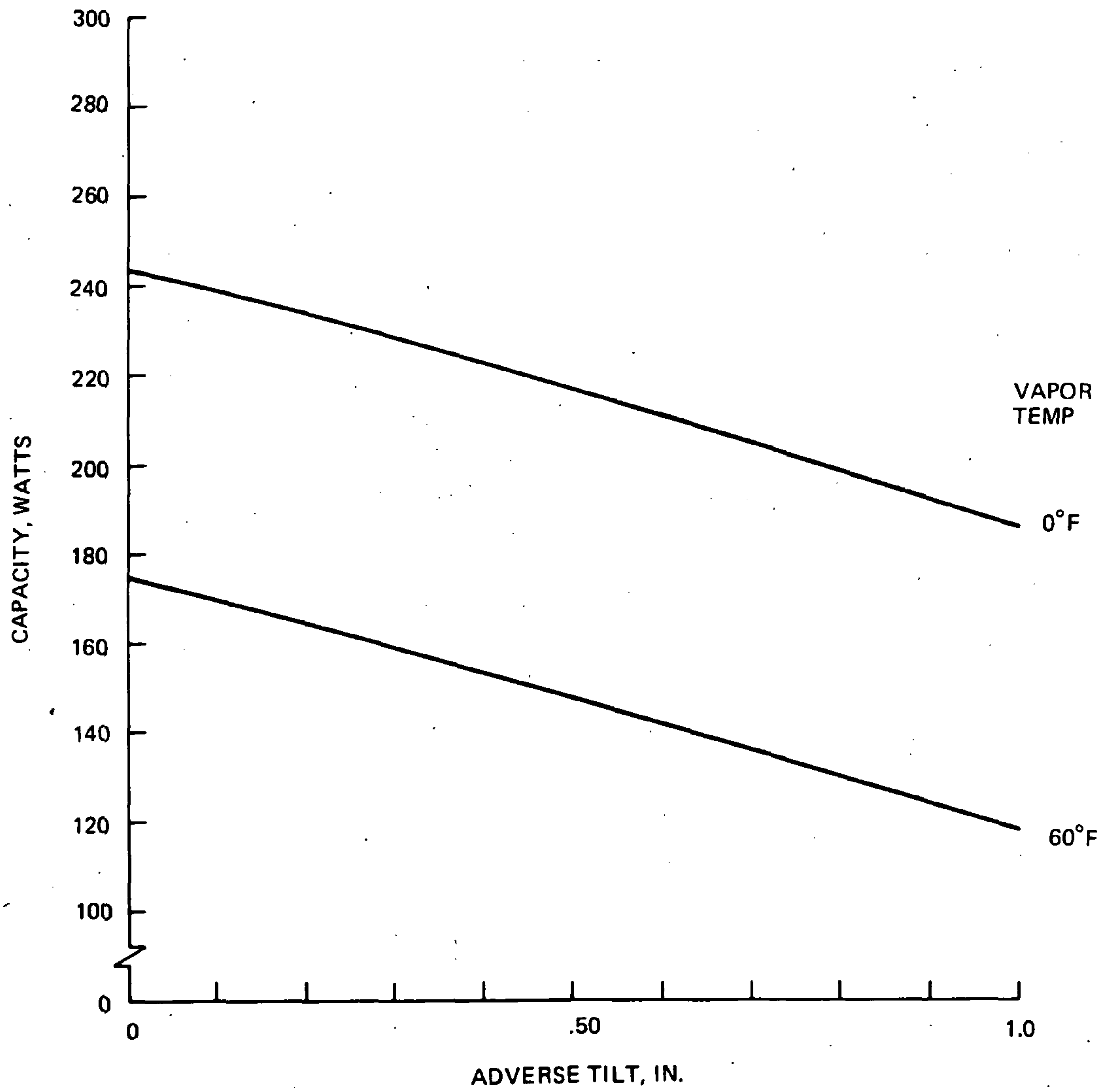


Fig. 4-5 Panel Feeder HP Predicted Performance

FOLDOUT FRAME 1

FOLDOUT FRAME 2

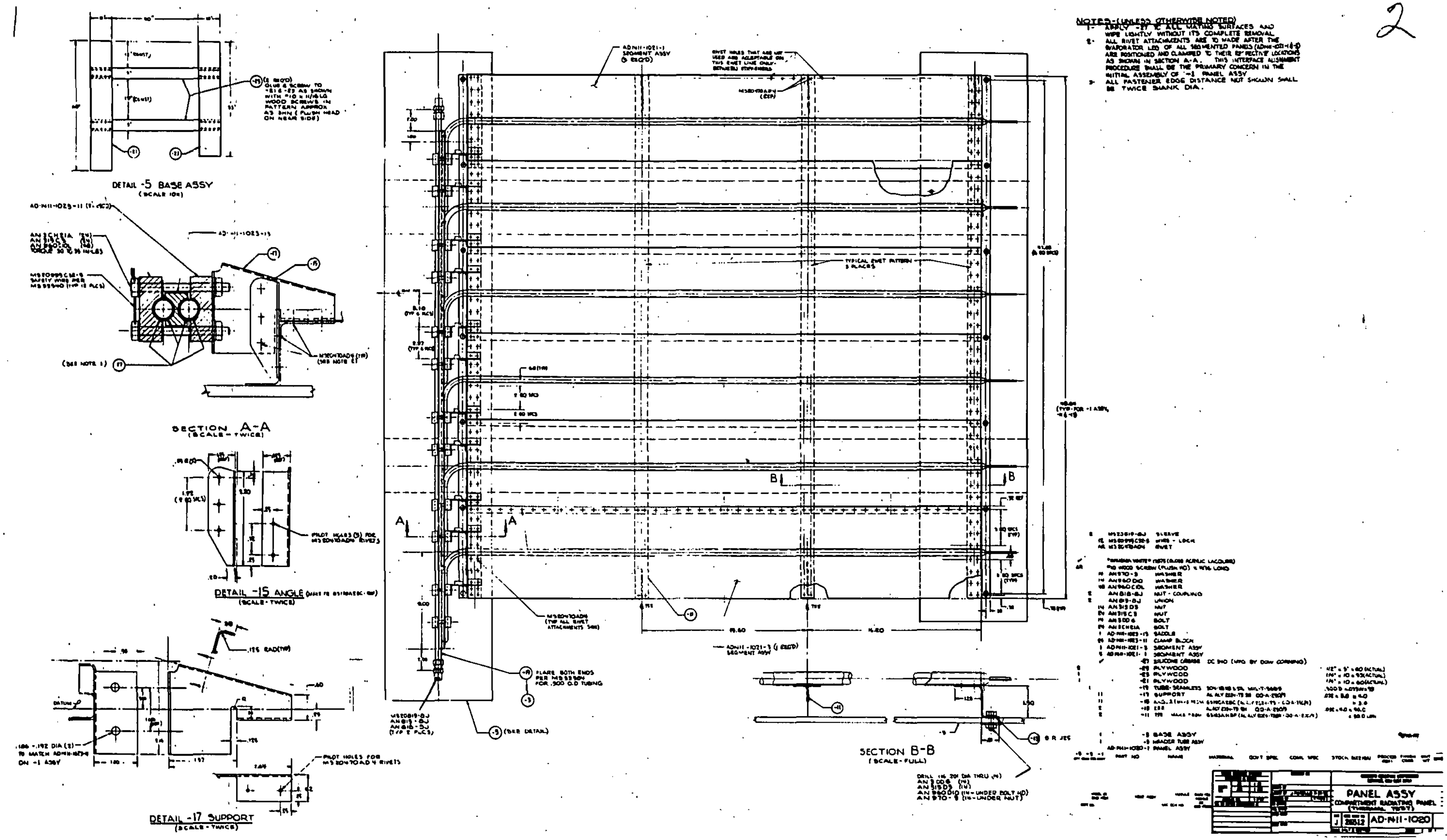


Fig. 4-6 HP Radiating Panel Assembly

Each fin subassembly is made of 20-mil thick 6061-T4 aluminum sheet. The radiating surface was coated with Chemglase Z306 — a black polyurethane paint with a nominal emittance of .9 that is easily applied and has excellent handling characteristics.

The general design features of the panel are summarized below.

- Material - Aluminum 6061-T4
- Area - 4 ft x 4 ft
- Thickness - .020 in.
- Emittance - .9
- Heat Pipes - 6 on 8-in. pitch

Figure 4-7 shows that fin effectiveness varies between .92 and .88 for respective variations in root temperature between -40°F and 40°F. Higher values of effectiveness are possible with thicker skin gauges, but the additional benefit is not significant. A 20 mil skin facilitates fabrication of subassemblies and results in a lighter panel.

The assembled heat pipe radiating panel, before instrumentation and painting, is shown in Fig. 4-8. The total weight of the assembly, including clamps, saddle block and tube, is 14.6 lb or .91 lb per ft^2 of radiator fin area.

4.2 FEEDER HP BENCH TEST RESULTS

All feeder HPs were individually tested at a tilt of .500-in. and a sink temperature of 55°F to verify at least a 50-watt capacity. In addition, feeder pipe no. 1 was tested at tilts of .25, .50, 1.0, 1.5 and 2.0 in. in both a straight (before bending) and L-shaped configuration. Pipe no. 1 was then vibration tested (see Appendix A) and rechecked to determine the resulting performance degradation.

Power was applied to the pipe with an electrical ribbon heater that was circumferentially wrapped around the 6 in. evaporator. The 4-ft long condenser section was cooled by submerging it in a cooling trough with running tap water. Each pipe was instrumented with 11 copper/constanan thermocouples as indicated in Fig. 4-9. After installation of the thermocouples, both the 6-in. evaporator and 3-in. transport sections were insulated with 1-in. thick Armaflex rubber insulation. It should be noted that the evaporator

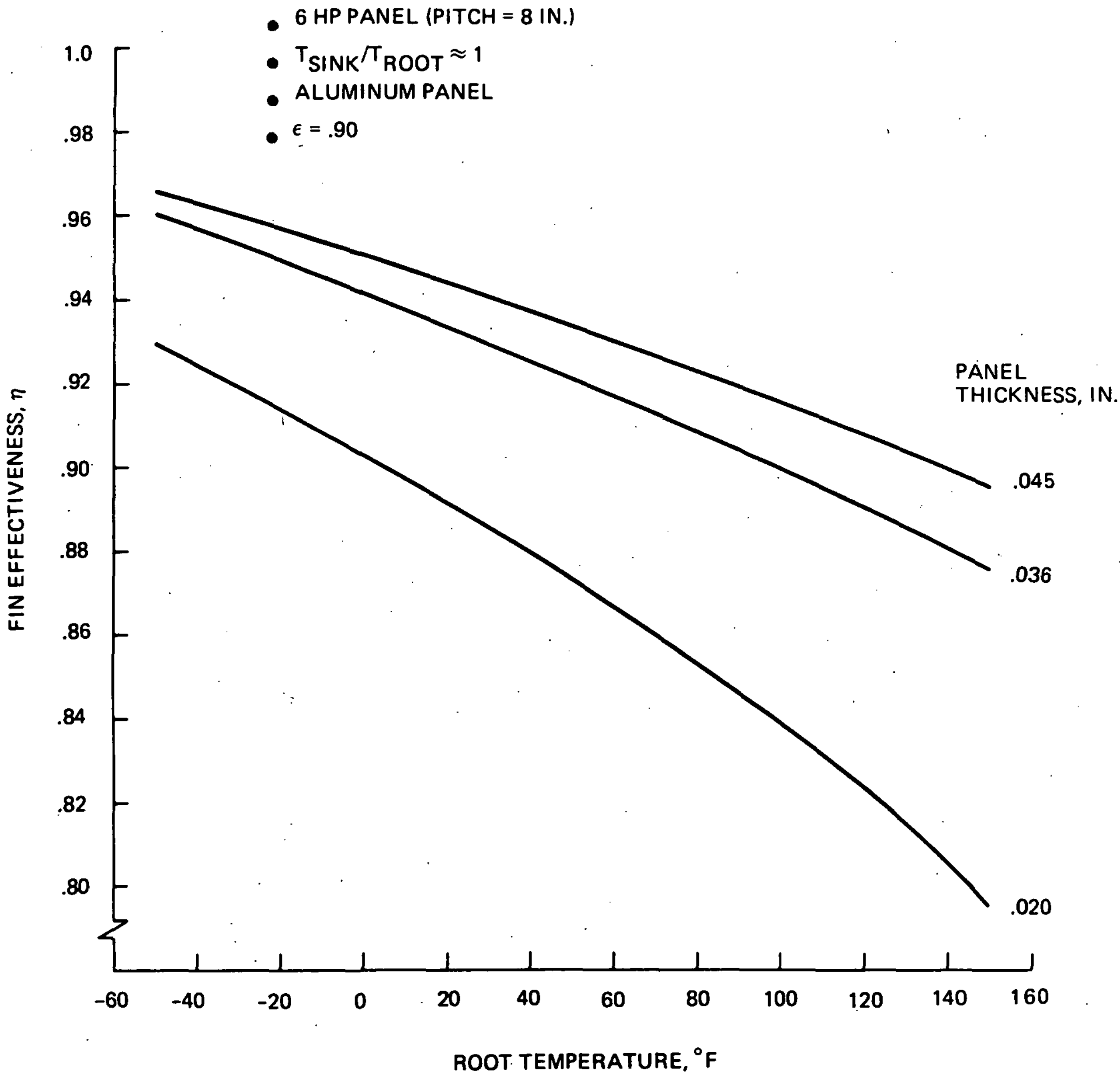


Fig. 4-7 HP Panel Fin Effectiveness

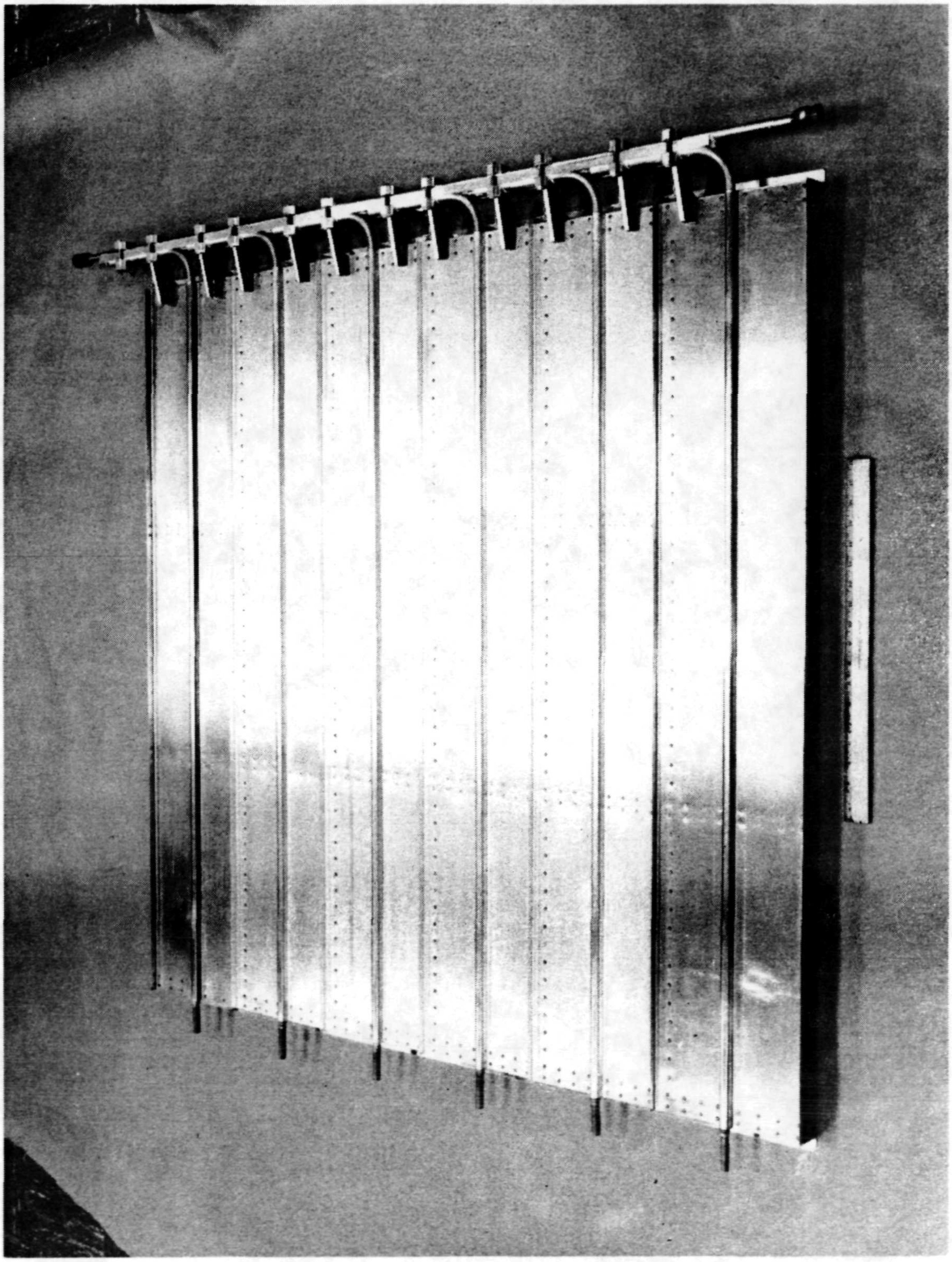


Fig. 4-8 HP Radiating Panel

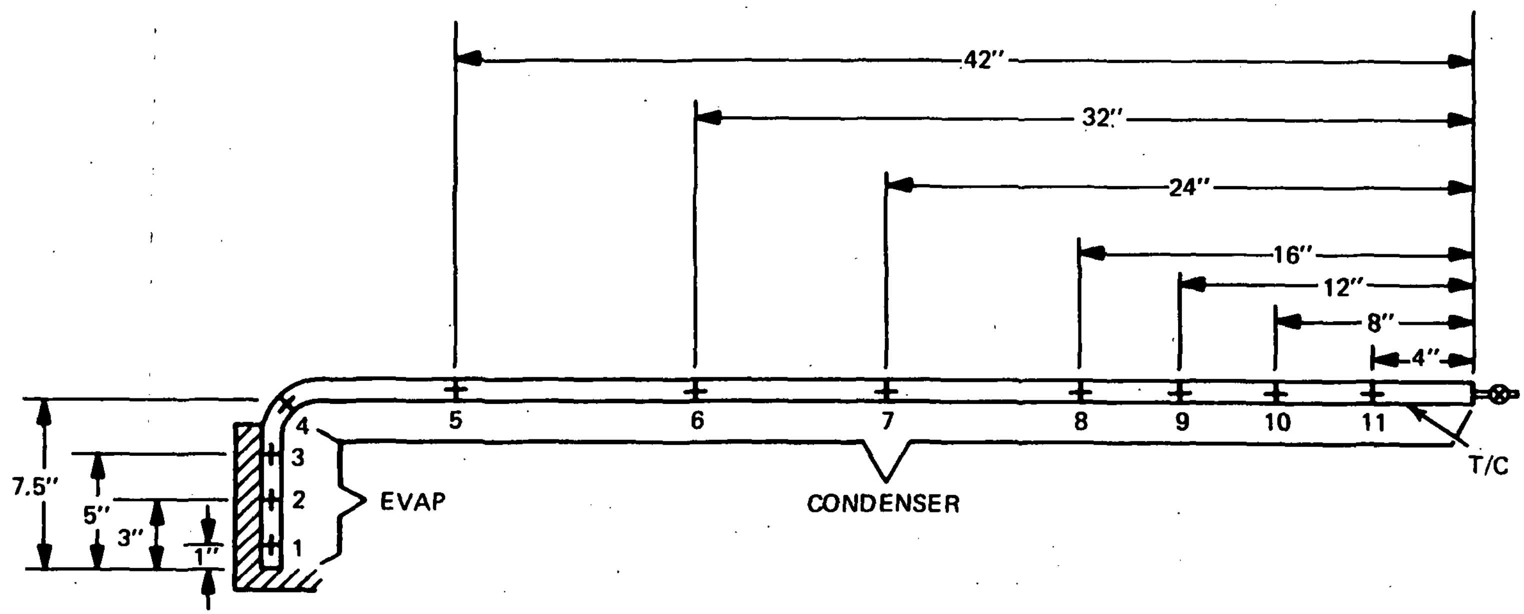


Fig. 4-9 Feeder HP Bench Test Instrumentation.

thermocouples were influenced by their close proximity to the electrical heater and therefore required judgement in interpretation.

Test results for pipe no. 1 show no performance degradation due to bending of the pipe. Figures 4-10 and 4-11 show a 230 watt capacity was achieved for both the straight and L-shaped pipe at a .500-in. tilt. Pre- and post-vibration test results are compared in Fig. 4-11 and Fig. 4-12. These comparisons show a noticeable degradation in performance after the equivalent of 100 shuttle missions. Maximum transport capacity decreased by about 50% (to 145 watts at .500-in. tilt) and the temperature difference between the evaporator and condenser sections increased (from 3°F to 6°F at 50 watts). The decrease in capacity is attributed to an increase in effective pore radius somewhere in the screening as a result of the severe vibration levels. The contact between the retainer legs and the wall was also adversely affected as evidenced by the increased ΔT.

Figure 4-13 summarizes the test results for all six feeder HPs and gives ΔT from evaporator to condenser as a function of load. All curves are for .500-in. tilt. At 50 watts, the ΔT is less than 5°F for all of the HPs.

Detailed data sheets for all of the feeder HP thermal bench tests are contained in Appendix F.

4.3 SYSTEM TEST RESULTS

The HP radiating panel was tested in a 7 x 7 ft end-loading thermal vacuum chamber that has a cold wall which is temperature controllable from -300°F to +300°F. The panel was suspended in the test chamber by four 3-ft long, 40-mil stainless steel wires located at each corner of the panel. It was positioned so that the fluid line and evaporator legs were level, while the ends of the condenser sections were 1/4 to 1/2 in. below the ends of the evaporators. A closed-loop hydraulic fluid system provided a controllable inlet temperature and flow rate to the panel.

A 25-layer blanket of aluminized mylar superinsulation was used to insulate the backside of the radiating fin. A double 25-layer blanket was used to wrap the hydraulic fluid line and evaporator sections to insulate them from the environment. All fluid lines and thermocouple bundles were likewise insulated to minimize heat leaks.

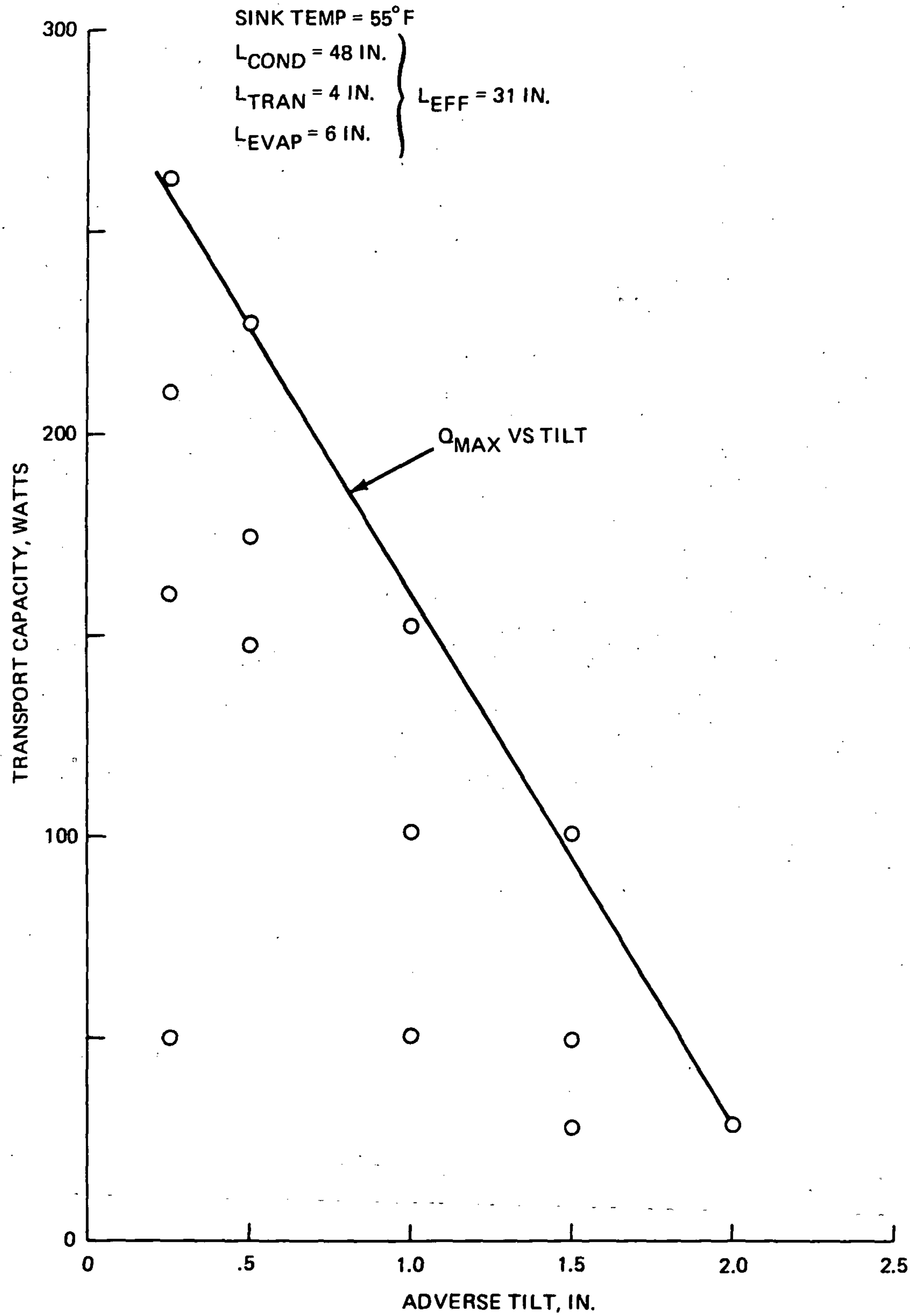


Fig. 4-10 Bench Test (Q vs Tilt) of Feeder HP No. 1, Straight Configuration

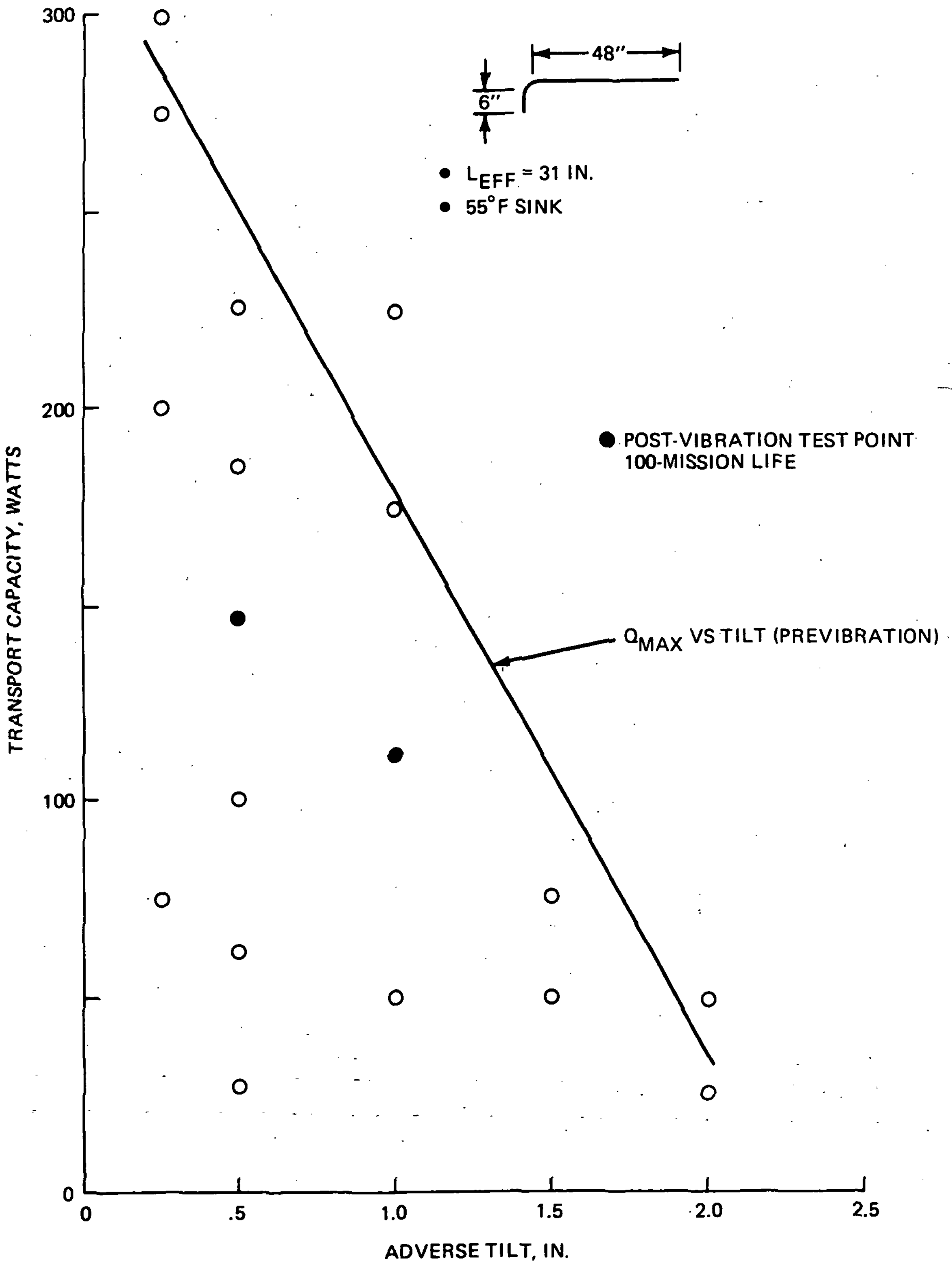


Fig. 4-11 Bench Test (Q vs Tilt) of Feeder HP No. 1, L-Shaped Configuration

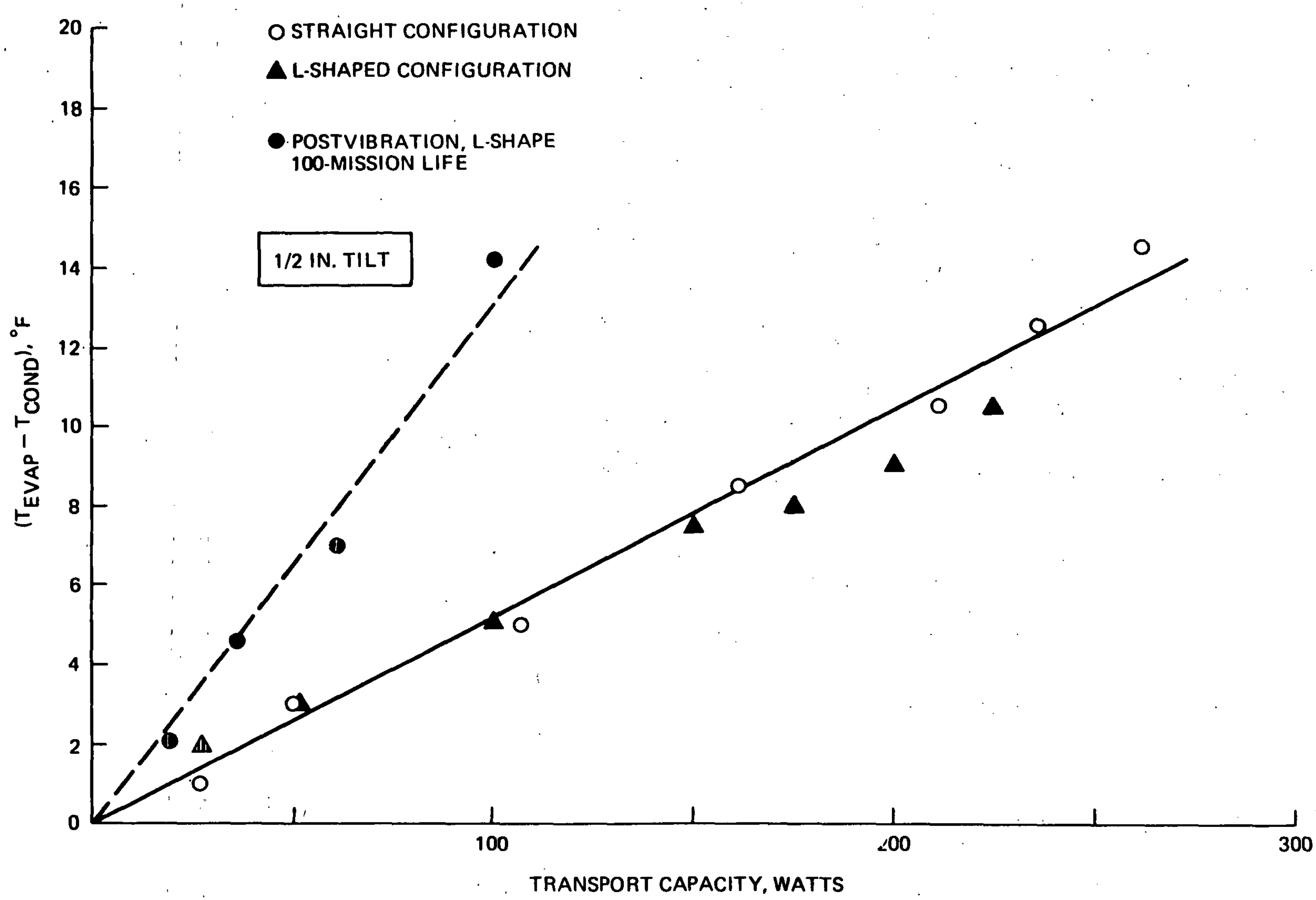


Fig. 4-12 Bench Test ($\Delta T_{E\text{-}C}$ vs Q) of Feeder HP No. 1

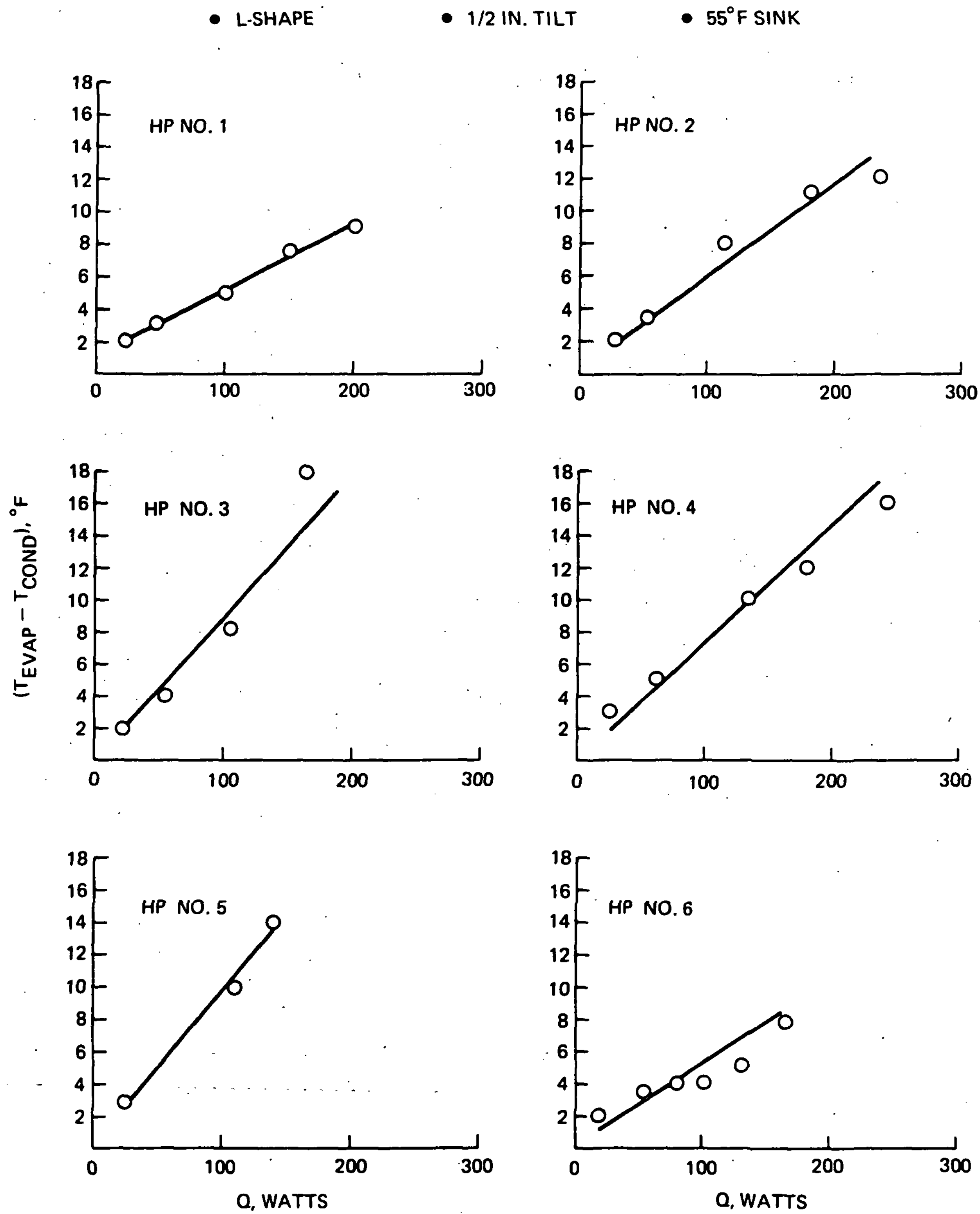


Fig. 4-13 Feeder HP Bench Test Data, HPs No. 1–6

The radiator panel was instrumented with 48 copper/constantan thermocouples. In addition, two immersion thermocouples were used to measure the fluid inlet and outlet temperatures and a differential millivolt reading was taken between them to determine the fluid ΔT across the panel. This value along with flow rate was used to calculate the net heat rejected from the system. A closed loop hydraulic fluid system provided a controllable inlet temperature and flow rate. The fluid loop and radiator installation are shown schematically in Fig. 4-14. An instrumentation diagram for the radiating panel system test is shown in Fig. 4-15. The fluid node measurement thermocouples were strapped onto the hydraulic fluid line with nylon tie straps and well insulated. The only immersion readings taken were slightly downstream of TC 1 (inlet) and upstream of TC 48 (outlet).

The assembled panel, after being instrumented and painted but before being insulated, is shown in Fig. 4-16. Random surface emittance measurements taken with a portable emissometer gave values ranging from .885 to .92 with most of the readings around .90. Figure 4-17 shows the fully insulated panel suspended from the chamber support rail awaiting insulation of the wire bundles and final alignment before being slid into the chamber enclosure.

The basic system test plan called for measuring fluid header and HP panel temperatures for various combinations of environment, flow rate and inlet temperature. Table 4-1 gives the test conditions that were run. They included three basic test series for -40°F, -20°F and 0°F cold wall temperatures. For each case, the hydraulic fluid flow rate was varied from .40 to 1.2 gpm (in .40 increments) with inlet temperatures of 30, 60 and 90°F at each setting.

Pretest performance predictions were made by writing the heat flux equations for the system, reducing them to a single fourth order polynomial, and solving the polynomial expression numerically for the panel root temperature. Once the panel root temperature is known for the specified boundary conditions, the temperatures at other points are determined using the applicable flux equations.

For the analysis, the panel consisted of 6 identical feeder pipe/radiating fin subassemblies clamped to a hydraulic fluid line header. Each segment (with its attached section of

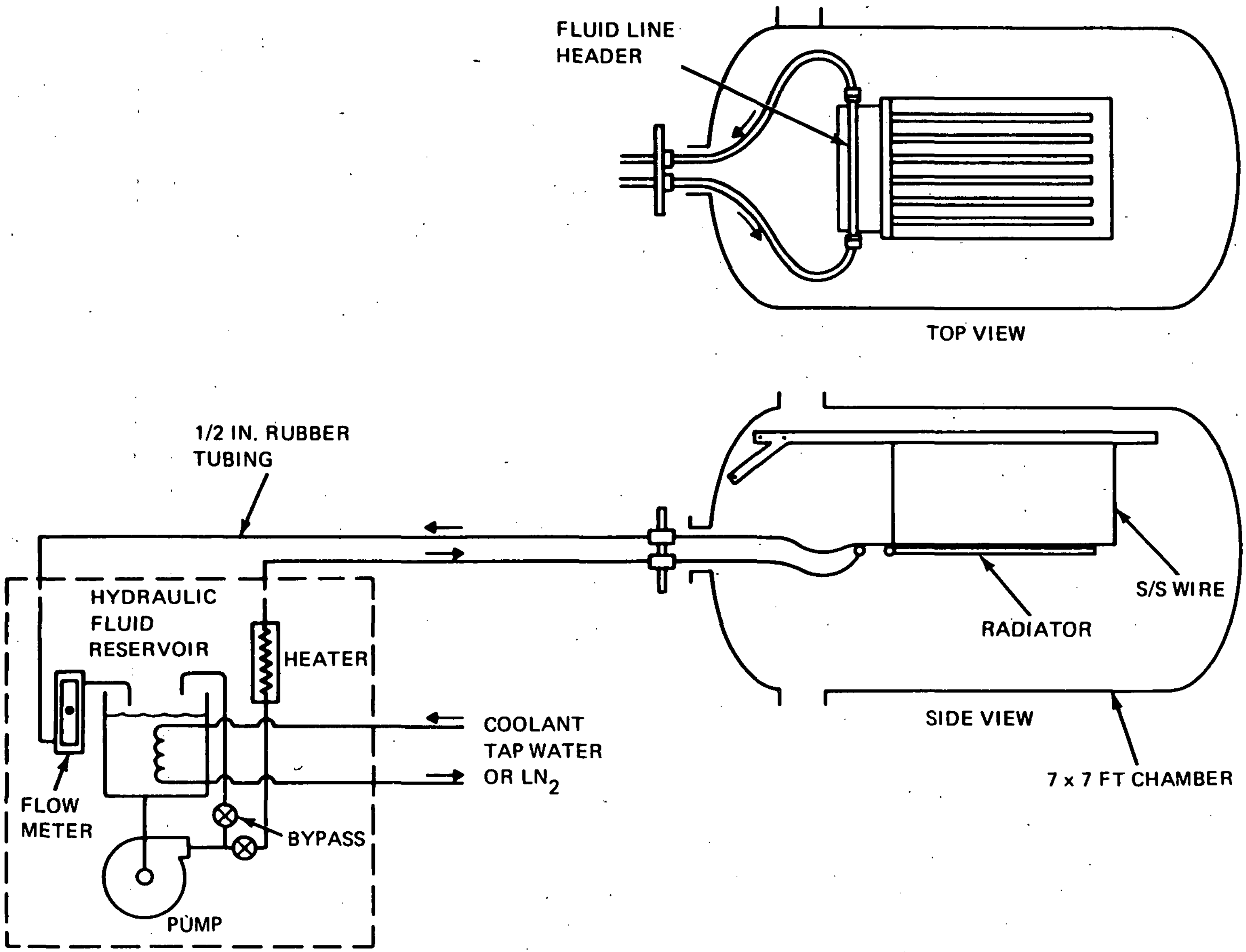


Fig. 4-14 Hydraulic Fluid Loop and HP Radiator Installation for System Test

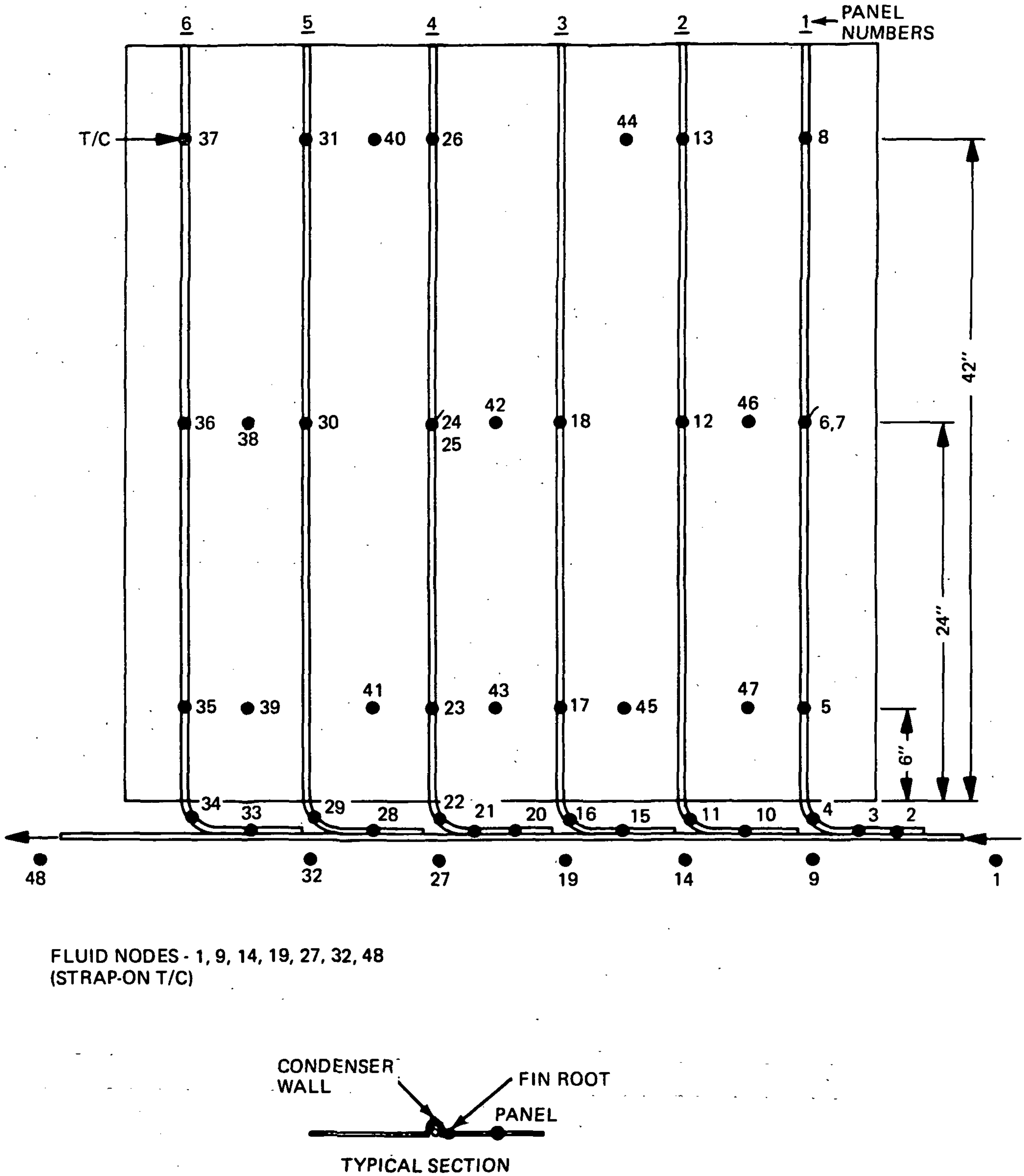


Fig. 4-15 System Test Thermocouple Locations

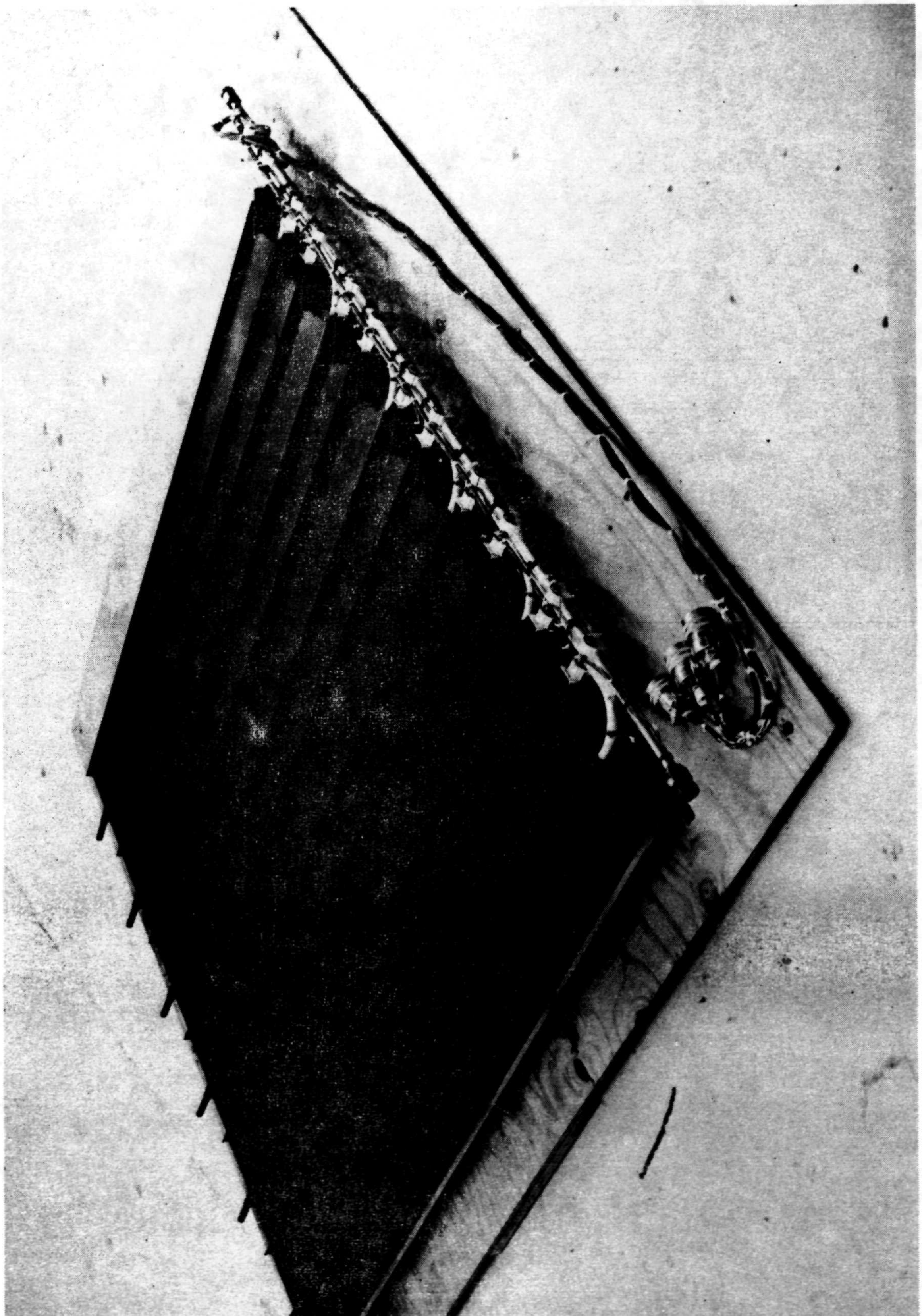


Fig. 4-16 HP Radiating Panel Before Insulation

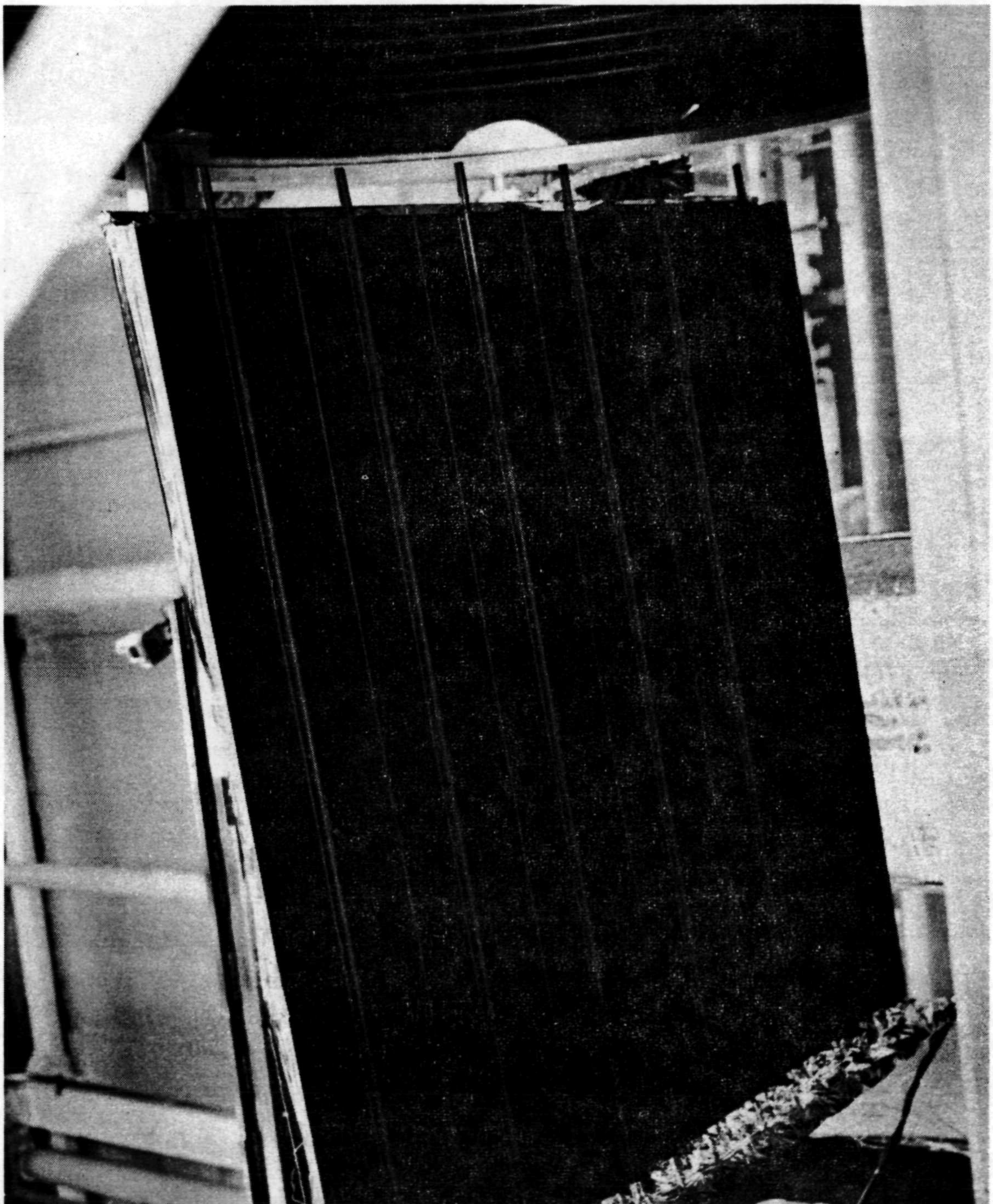


Fig. 4-17 HP Radiating Panel in Thermal Vacuum Chamber

hydraulic line) was analyzed separately, the system subsection is shown in schematic form in Figure 4-18.

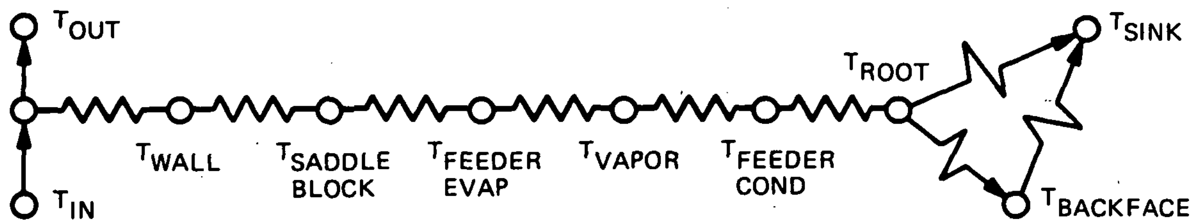


Fig. 4-18 Panel Segment Thermal Model

The following equations describe the heat transfer paths throughout the system.

Heat Transfer from Fluid

$$q_{IN} = \dot{m}c_p \left(T_{IN} - T_{OUT}\right) \tag{1}$$

Fluid to S/S Tube Wall

$$q_{IN} = h_{Fluid}\, A_{\substack{WALL\\ EFFECT.}} \left(\frac{T_{IN} - T_{OUT}}{\ln\left(\dfrac{T_{IN} - T_{WALL}}{T_{OUT} - T_{WALL}}\right)} \right) \tag{2}$$

S/S Tube to Saddle Block

$$q_{IN} = h_{INTERFACE\ 1}\, A_{INTERFACE\ 1} \left(T_{WALL} - T_{BLOCK}\right) \tag{3}$$

Saddle Block to Feeder Evaporator

$$q_{IN} = h_{INTERFACE\ 2}\, A_{INTERFACE\ 2} \left(T_{BLOCK} - T_{EVAP}\right) \tag{4}$$

Evaporator to HP Vapor

$$q_{IN} = h_{EVAP}\, A_{\substack{EVAP\\ EFFECT.}} \left(T_{EVAP} - T_{VAPOR}\right) \tag{5}$$

HP Vapor to Feeder Condenser

$$q_{IN} = h_{COND}\, A_{\substack{COND\\ EFFECT.}} \left(T_{VAPOR} - T_{COND}\right) \tag{6}$$

Feeder Condenser to Fin Root

$$q_{IN} = h_{POLY} A_{POLY} \left(T_{COND} - T_{ROOT} \right) \tag{7}$$

For the radiation couplings:

$$q_{IN} = \sigma A_{PANEL} \left[\eta_f \epsilon_{PANEL} \epsilon_{SINK} \left(T^4_{ROOT} - T^4_{SINK} \right) + \epsilon_{\substack{INSULATION \\ (EFFECTIVE)}} \left(T^4_{ROOT} - T^4_{BACK} \right) \right] \tag{8}$$

$$\epsilon_{\substack{INSULATION \\ (EFFECTIVE)}} \left(T^4_{ROOT} - T^4_{BACK} \right) = \epsilon_{BACKFACE} \epsilon_{SINK} \left(T^4_{BACK} - T^4_{SINK} \right) \tag{9}$$

These equations were solved for T_{ROOT} using the Newton-Raphson iterative technique. Once T_{ROOT} is known, all other system unknowns are easily calculated from the aforementioned steady-state relationships. A listing of the computer program that was used in the analysis is contained in Appendix G.

The results of the pretest predictions for the system tests are summarized in Table 4-2 for a typical segment of the panel and in Fig. 4-19 for the system as a whole. These predictions reflect the following nominal system parameters:

Parameter	Value (BTU/hr ft^2 °F)
$h_{interface}$ (evaporator/header)	1000
$h_{interface}$ (condenser/fin)	500
$h_{evaporator}$	2700
$h_{condenser}$	3500

Also, fully developed laminar flow with a Nusselt number of 3.66 was assumed for the hydraulic fluid in the smooth wall stainless steel tube. This is consistent with the high Prandtl number and the very low Reynolds number (≈20) of the fluid and makes the theoretical system heat rejection rate essentially independent of flow rate.

By far the greatest portion of the temperature drop between fluid inlet and radiator fin root takes place in the hydraulic fluid itself since it has extremely poor thermal

• FULLY DEVELOPED LAMINAR FLOW ASSUMED

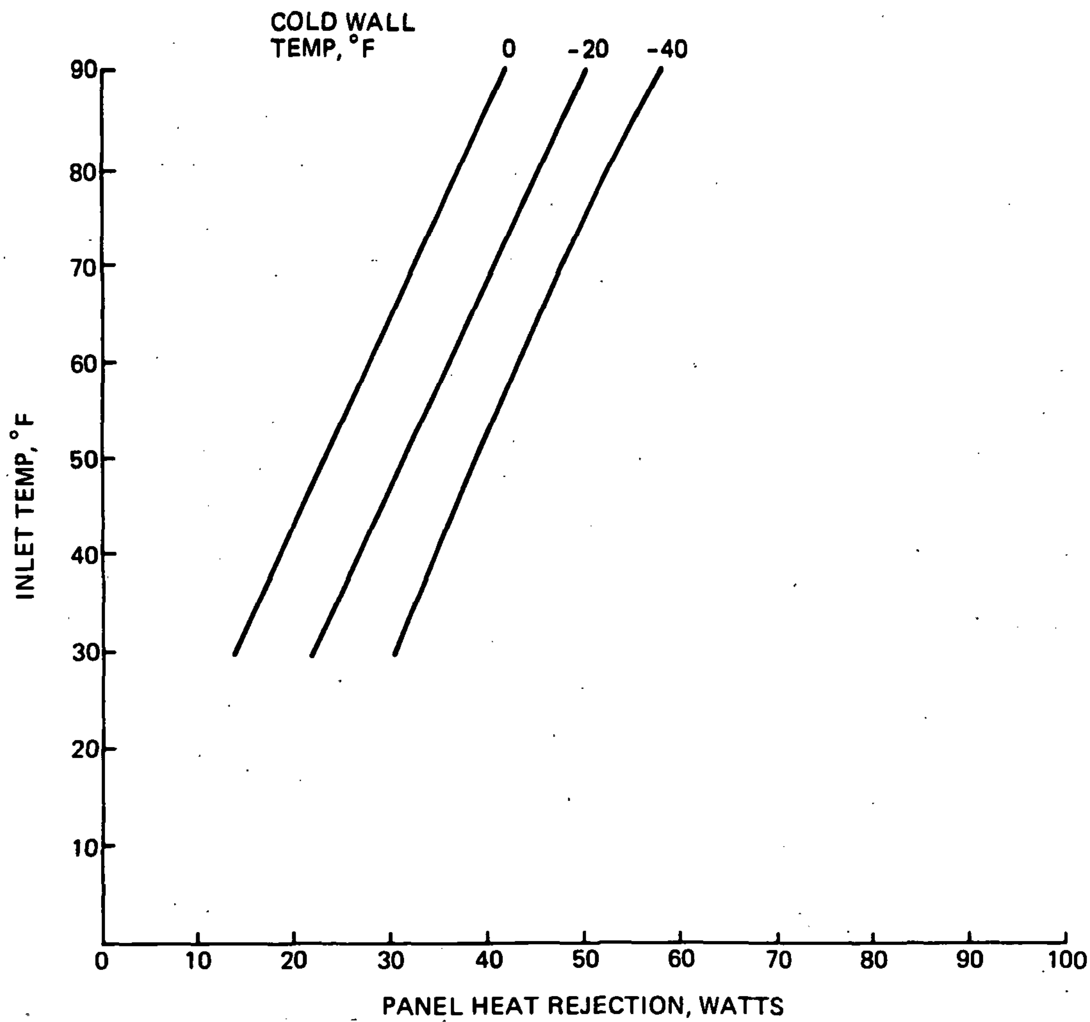


Fig. 4-19 HP Radiating Panel Predicted System Performance

conductivity that results in a low convective heat transfer film coefficient. If required, the system's performance can be greatly improved by simply finning the tube ID. Figure 4-20, shows the ΔT between fluid and fin root as a function of panel heat rejection to a -20°F environment for both the smooth tube case tested and a finned cold plate modification. However, finning represents an incursion on the hydraulic system and was groundruled out for this particular application. But its utility should still be remembered for situations where performance is the overriding consideration.

The results of the system tests proved that the HP radiating panel can be used to extract waste heat from a fluid line through a simple mechanical bolted connection that has minimum impact on the fluid system. In general, the HP radiating panel extracted between 50 and 120 watts from the hydraulic fluid, with a 60 to 90°F inlet, and rejected it to a -40 to 0°F enclosure. All interface attachments were purely mechanical and the hydraulic fluid line was a smooth-wall 1/2-in. OD stainless steel tube. It had no internal finning to increase heat transfer.

The net heat rejection of the panel was determined by two methods: one based on the measured fluid heat loss ($\dot{m}C_p \Delta T$) and the other based on the average panel fin temperature and the environment. Ideally, both values should be the same, but in fact they were not. There was a good deal of fluctuation in the digital millivolt reading of the fluid ΔT across the panel during the steady state run, thus, the value recorded represents a visual average. The panel fin temperatures on the other hand were very stable. For this reason, the net heat rejection as determined by panel temperatures is considered more representative of actual system performance.

Test results are summarized by representing panel heat rejection as a function of hydraulic fluid flow rate for the various inlet and cold wall temperatures. Figure 4-21 presents the panel heat rejection based on fluid temperature measurements and shows behavior that is far removed from predictions. That is, the heat rejection appears to be a strong function of flow rate, which indicates definite non-laminar flow conditions. The net heat rejection as determined from panel temperatures (see Fig. 4-22) is more in line with predictions and variation with flow rate is slight. This supports the laminar flow contention. Figure 4-22 also shows performance points obtained when the inlet

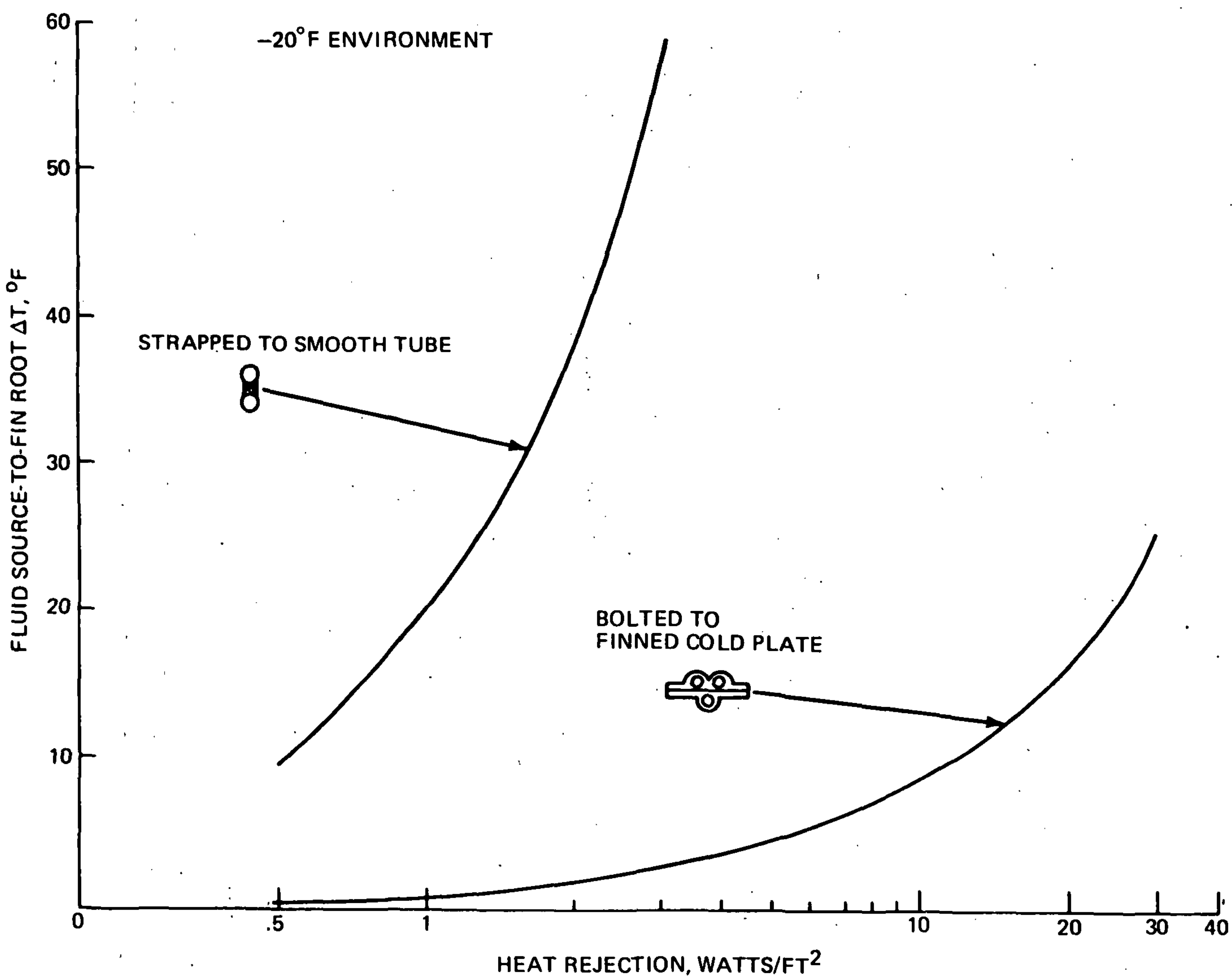


Fig. 4-20 Strap-On HP Radiating Panel Performance Comparison

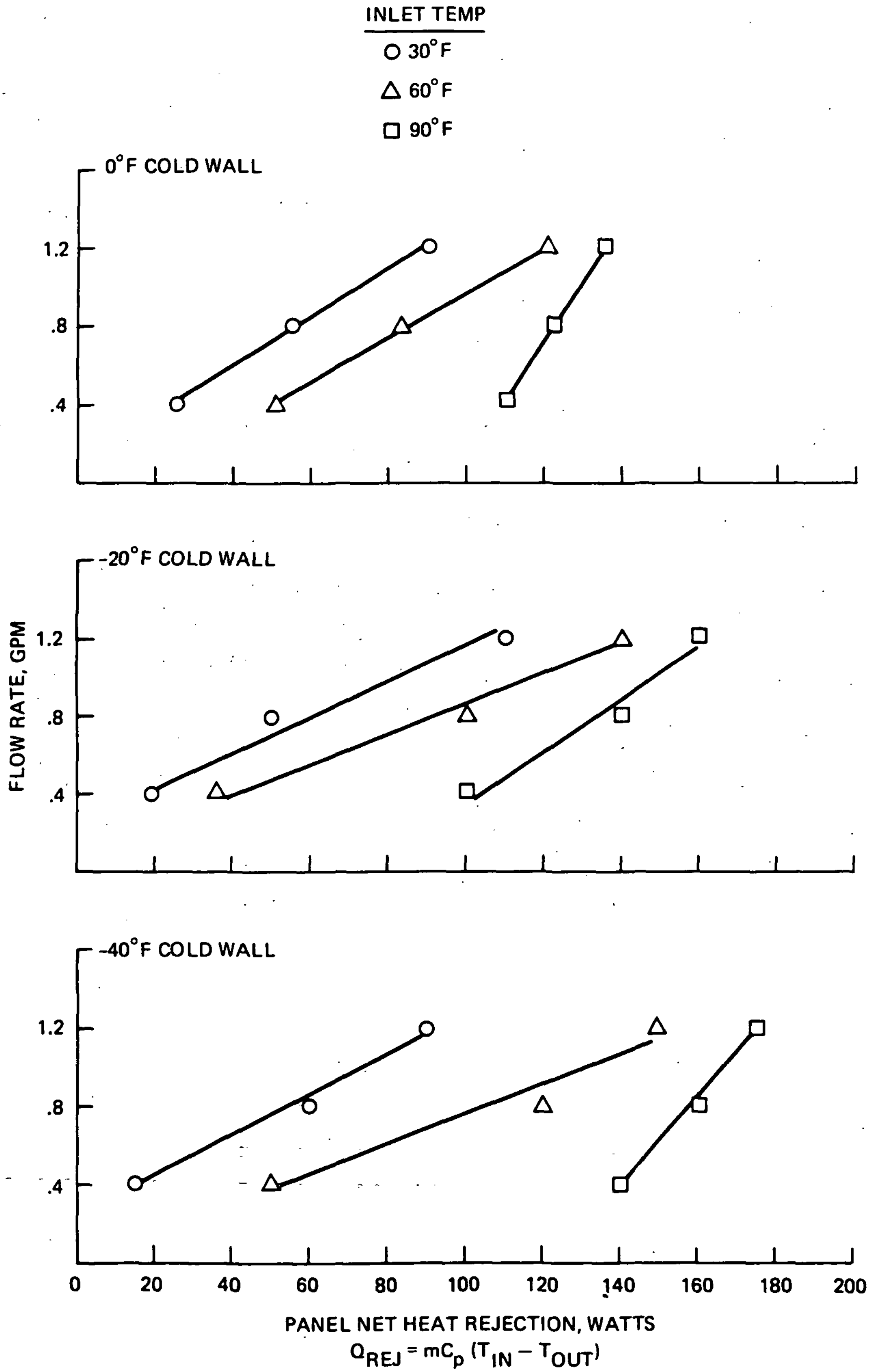
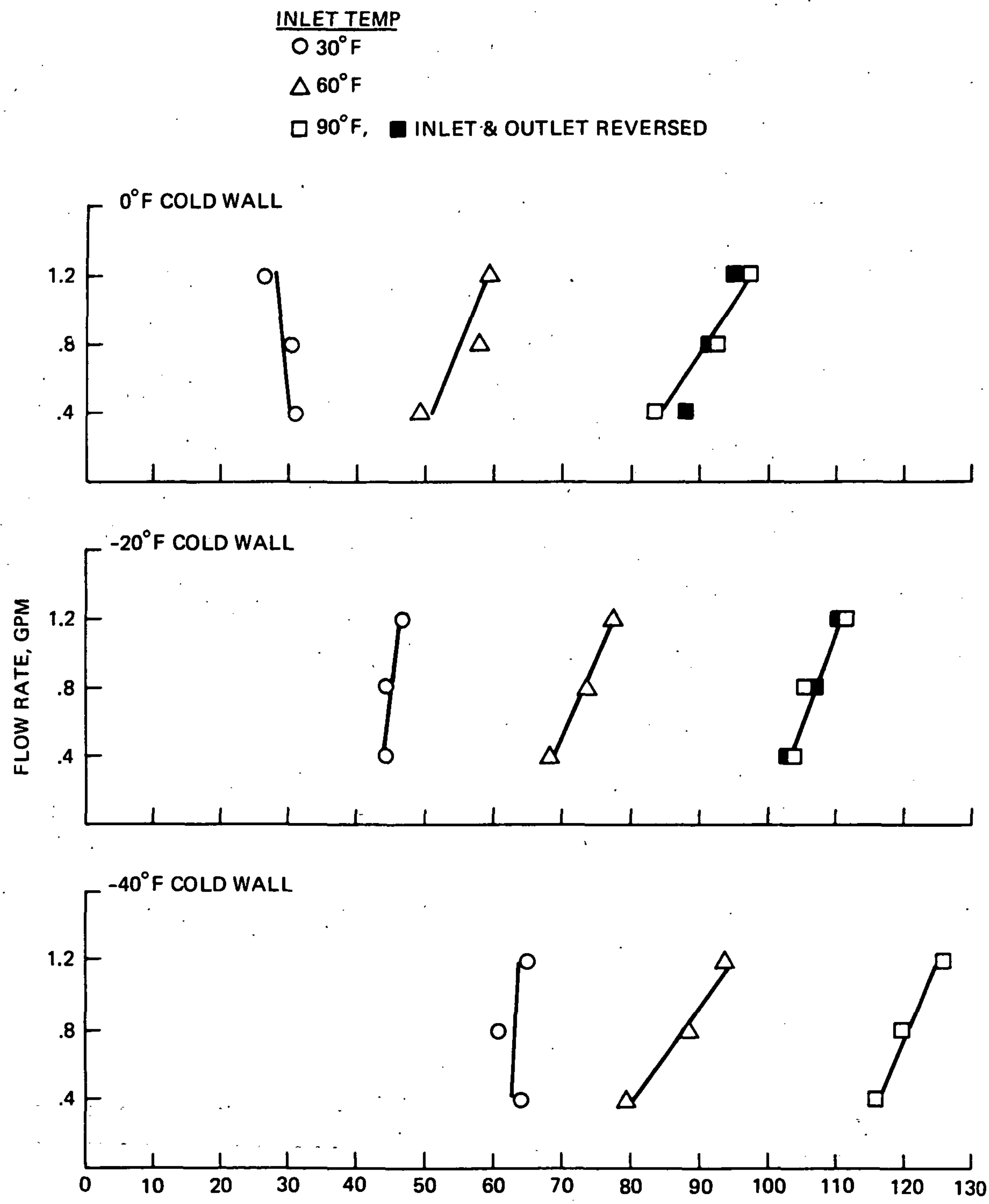


Fig. 4-21 HP Panel Heat Rejection Based on Coolant Flow



$$Q_{REJ} = \epsilon_p \epsilon_w (\sigma \overline{T}_p^4 - \sigma T_w^4)$$

Fig. 4-22 HP Panel Heat Rejection Based on Panel Temperatures

and outlet connections were reversed. This caused no noticeable effect on heat rejection; panel temperature distributions were simply reversed. Based on the panel temperature data, system heat rejection varies from 80 to 120 watts, depending upon the environment, for a realistic on-orbit inlet temperature of 90°F.

Table 4-3 gives the average panel fin temperatures that were calculated for each test run. The corresponding detailed temperature data that was obtained during system testing is contained in Appendix H.

TABLE 4-1 RADIATION PANEL SYSTEM TEST CONDITIONS

TEST NO.	COLD WALL TEMP, F°	FLOW RATE, GPM	INLET TEMP, F°
1	-40	.40	30
2	-40	.40	60
3	-40	.40	90
4	-40	.80	30
5	-40	.80	60
6	-40	.80	90
7	-40	1.2	30
8	-40	1.2	60
9	-40	1.2	90
10	-20	.40	30
11	-20	.40	60
12	-20	.40	90
13	-20	.80	30
14	-20	.80	60
15	-20	.80	90
16	-20	1.2	30
17	-20	1.2	60
18	-20	1.2	90
19	0	.40	30
20	0	.40	60
21	0	.40	90
22	0	.80	30
23	0	.80	60
24	0	.80	90
25	0	1.2	30
26	0	1.2	60
27	0	1.2	90

TABLE 4-2 PREDICTED PANEL TEMPERATURES

Typical Panel Segment No. 4	Q_{in} (watts)	Q_{Leak} (watts)	T_{Evap}		T_{Trans}		T_{Cond}		T_{Root}		$T_{Mid-Panel}$	
			^oF	^oK	^oF	^oK	^oF	^oK	^oF	^oK	^oF	^oK
1	5.02	0.09	-17.2	245.8	-17.4	245.7	-17.4	245.7	-17.6	245.6	-20.4	244.1
2	7.25	0.13	-8.2	250.8	-8.4	250.7	-8.5	250.7	-8.7	250.5	-12.6	248.4
3	9.51	0.17	0.6	255.7	0.2	255.5	0.2	255.5	-0.2	255.3	-5.2	252.5
4	5.05	0.09	-17.1	245.9	-17.3	245.8	-17.3	245.7	-17.5	245.7	-20.4	244.1
5	7.29	0.13	-8.0	250.9	-8.3	250.8	-8.3	250.8	-8.5	250.6	-12.5	248.4
6	9.56	0.17	0.8	255.8	0.4	255.6	0.4	255.6	0.1	255.4	-5.0	252.6
7	5.06	0.09	-17.1	245.9	-17.3	245.8	-17.3	245.8	-17.4	245.7	-20.2	244.2
8	7.30	0.13	-7.9	251.0	-8.2	250.8	-8.2	250.8	-8.4	250.7	-12.5	248.4
9	9.58	0.17	0.8	255.8	0.5	255.6	0.4	255.6	0.2	255.5	-4.9	252.7
10	3.71	0.07	-4.9	252.6	-5.0	252.6	-5.0	252.6	-5.2	252.5	-7.2	251.4
11	5.99	0.11	3.7	257.4	3.5	257.3	3.4	257.3	3.2	257.2	-0.2	255.3
12	8.30	0.15	11.9	262.0	11.6	261.8	11.6	261.8	11.3	261.6	6.7	259.1
13	3.73	0.07	-4.8	252.7	-5.0	252.6	-5.0	252.6	-5.1	252.5	-7.2	251.4
14	6.02	0.11	3.8	257.5	3.6	257.4	3.6	257.3	3.4	257.2	0.0	255.4
15	8.35	0.15	12.1	262.1	11.8	261.9	11.8	261.9	11.5	261.8	6.8	259.2
16	3.74	0.07	-4.8	252.7	-4.9	252.6	-5.0	252.6	-5.1	252.6	-7.1	251.4
17	6.03	0.11	3.8	257.5	3.6	257.4	3.6	257.4	3.4	257.3	0.0	255.4
18	8.36	0.15	12.2	262.1	11.9	262.0	11.8	261.9	11.6	261.8	6.9	259.2
19	2.30	0.04	8.4	260.0	8.3	260.0	8.3	260.0	8.2	259.9	6.9	259.2
20	4.63	0.08	16.5	264.5	16.3	264.4	16.3	264.4	16.1	264.3	13.6	262.9
21	6.99	0.13	24.3	268.9	24.0	268.7	24.0	268.7	23.7	268.5	20.0	266.5
22	2.31	0.04	8.4	260.1	8.3	260.0	8.3	260.0	8.3	260.0	7.0	259.3
23	4.66	0.08	16.6	264.6	16.4	264.5	16.4	264.5	16.2	264.4	13.7	263.0
24	7.03	0.13	24.4	268.9	24.1	268.8	24.1	268.8	23.9	268.7	20.1	266.6
25	2.32	0.04	8.5	260.1	8.4	260.0	8.4	260.0	8.3	260.0	7.0	259.3
26	4.67	0.09	16.6	264.6	16.4	264.5	16.4	264.5	16.3	264.4	13.7	263.0
27	7.04	0.13	24.5	269.0	24.2	268.8	24.2	268.8	24.0	268.7	20.3	266.7

TABLE 4-3 AVERAGE PANEL FIN TEMPERATURES

GPM	INLET TEMP, °F	AVG PANEL FIN TEMP, °F COLD WALL TEMP -40°F	-20°F	0°F
.4	30	-10.5	-1.6	11.5
	60	-4.2	7.6	18.1
	90	9.9	20.4	29.7
.8	30	-11.9	-1.6	11.4
	60	-.5	9.6	21.1
	90	11.3	20.8	32.6
1.2	30	-10.2	-.55	9.9
	60	1.5	11.0	21.6
	90	13.4	22.9	34.0

Section 5

HEAT PIPE AUGMENTED COLD RAIL

The HP augmented cold rail uses a HP to extend the capabilities of a conventional flight-proven thermal control system — the fluid cold rail. Fluid cold rails were used to cool electrical equipment onboard Apollo spacecraft and are planned for use on the shuttle. Some of the flange-mounted electronics modules proposed for the shuttle might have heat dissipations of 40 watts/linear in./side, a value 16 times greater than the design values in the Apollo vehicle and exceeding the capability of the simple fluid cold rails. Using a HP at the center of a standard rail increases the local power density capability by diffusing the heat input over the entire length of rail. This permits high power modules to be integrated within the same cooling circuits as more conventional equipment.

As illustrated in Fig. 5-1, the HP augmented cold rail consists of an aluminum extrusion that contains two internally finned fluid passages surrounding a centrally positioned HP. Plates similar to the flanges on the boxes of rack-mounted electronics are bolted to the cold rail flanges. Heat applied to their outboard edges provides a realistic heat input to the cold rail. Cooling is provided by pumping coolant fluid (water) through the two fluid passages in the rail, exactly duplicating actual operating conditions. Heat flows from the equipment flange, across the bolted interface, and into the cold rail flange. From there, some heat is conducted directly to the finned fluid passages and the remainder goes into the central HP where it is transferred to the fluid at other points along the rail.

5.1 DESIGN DETAILS

5.1.1 Requirements

The HP augmented cold rail was designed to meet the following requirements:

- Similar in design to conventional fluid cold rails; 20 inch nominal rail length
- Compatible with state-of-the-art electronic packaging.
- Use of non-toxic HP working fluid

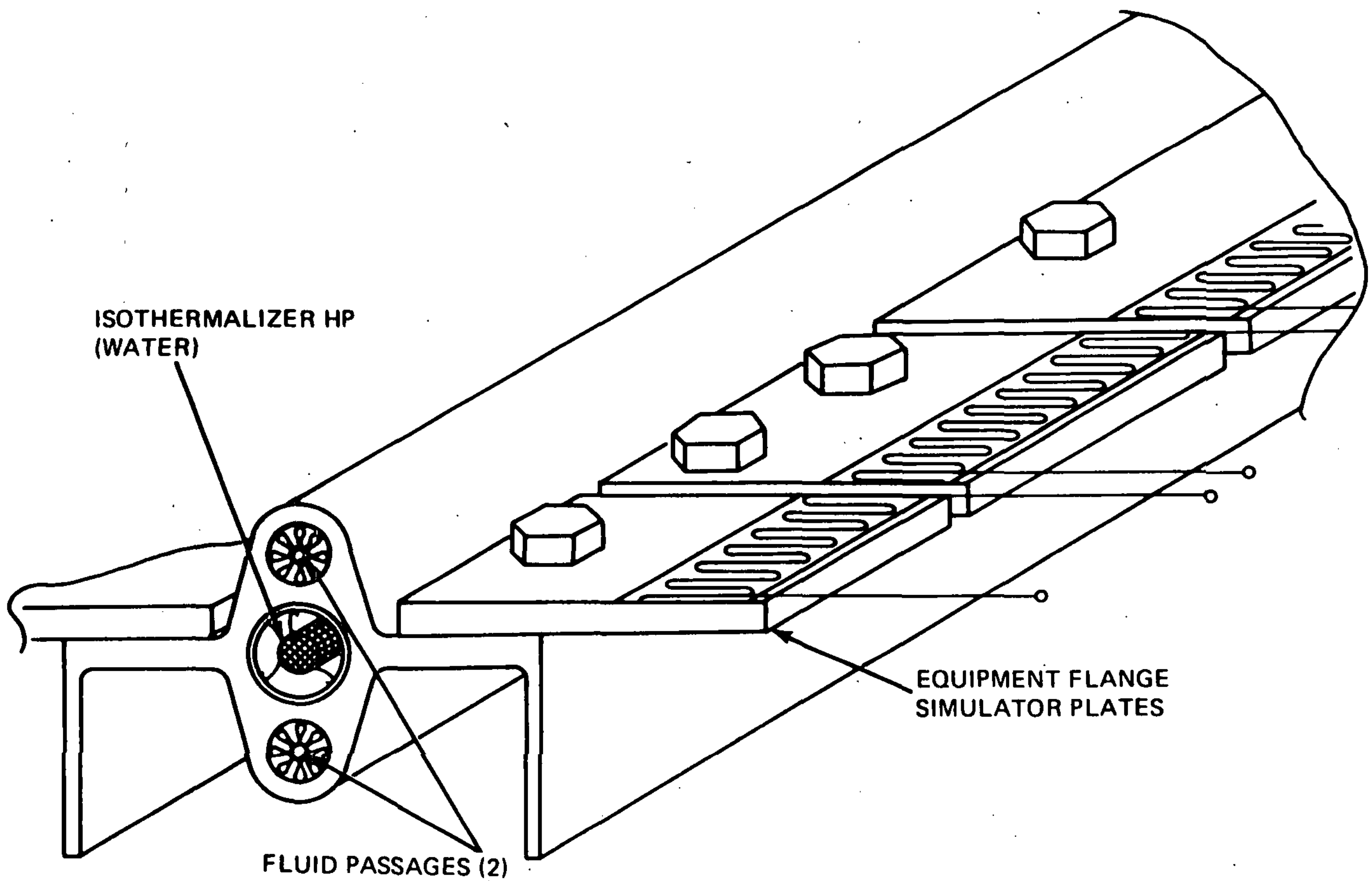


Fig. 5-1 HP Augmented Cold Rail

- Average load capacity over the entire length of the rail to be 4 watts/linear inch/side with one fluid passage operating; 8 watts/linear inch/side with both passages operating
- Maximum local rail capacity (over a two-inch section) to be 40 watts/linear inch
- Maximum design coolant fluid inlet and outlet temperatures of 70°F and 100°F, respectively
- Maximum cold rail total load = 320 watts
- Maximum equipment flange root temperature = 140°F

5.1.2 Design

Figure 5-2 presents the design details for the heat pipe augmented cold rail. It is made from a simple flanged aluminum extrusion that contains three internal passages; a central 1/2-in. diameter core for the water HP, and two 3/8-in. diameter openings for the primary coolant fluid. The two 3/8-in. flow passages are internally finned to enhance heat transfer to the primary coolant, which in this case is water.

Water was selected as the HP working fluid since it meets the non-toxic requirement for use in manned areas and it has an excellent performance figure of merit. All HP components were fabricated from copper for compatibility with water. Aluminum could not be used because of the gas that is generated when in contact with water. After assembly, all copper parts were treated with an Ebonol-C coating to enhance the wettability of the surfaces and permit proper heat pipe operation. The Ebonol-C coating process was selected because of prior experience and proven results with it. The process has extensive industrial use and is covered in detail by military specifications (MIL-F-495, Type III).

The requirement for a copper envelope for the HP made it necessary to bond a copper tube to the aluminum extrusion in a manner that minimized the interface thermal resistance. This was done by hydraulically pressurizing a snug-fitting copper tube at 13,000 psi so that it plastically deforms while elastically deforming the surrounding aluminum. When the pressure is relieved, the aluminum behaves elastically and clamps down around the copper tube on the way back to its original shape. A thin coating of silicone oil is used to help tube insertion and to act as an interstisial filler.

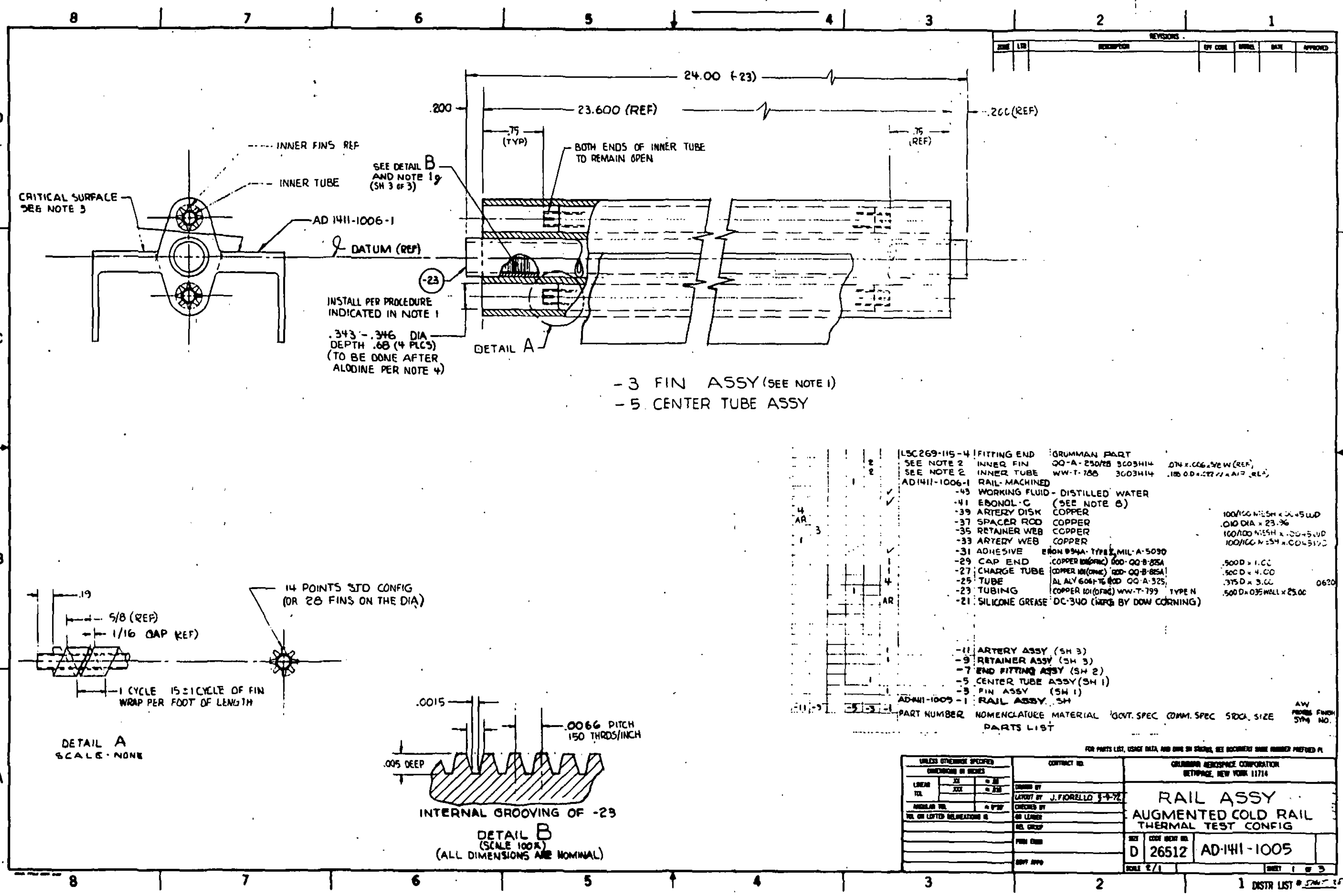


Fig. 5-2 HP Augmented Cold Rail Assembly (Sheet 1 of 3)

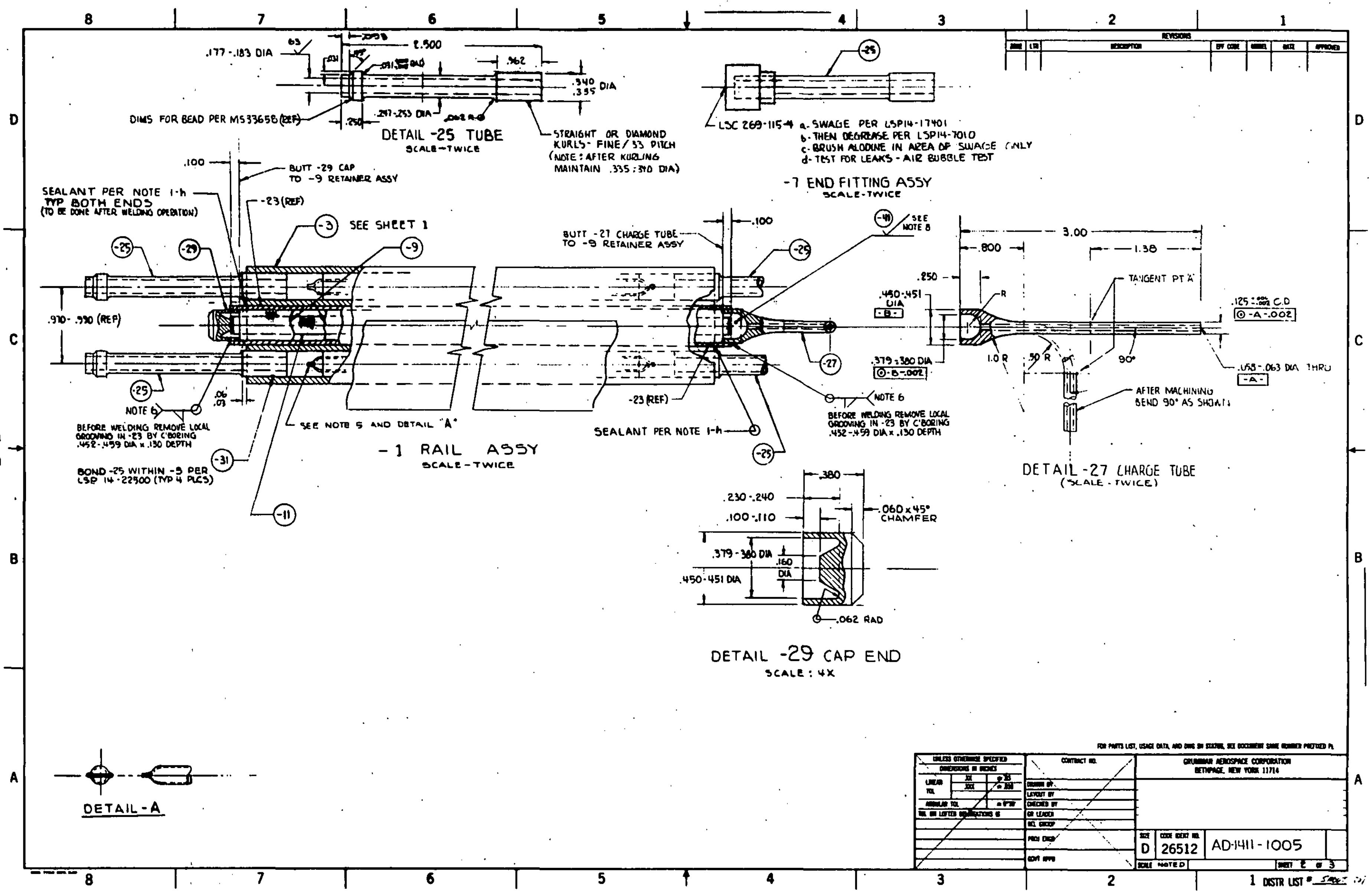


Fig. 5-2 HP Augmented Cold Rail Assembly (Sheet 2 of 3)

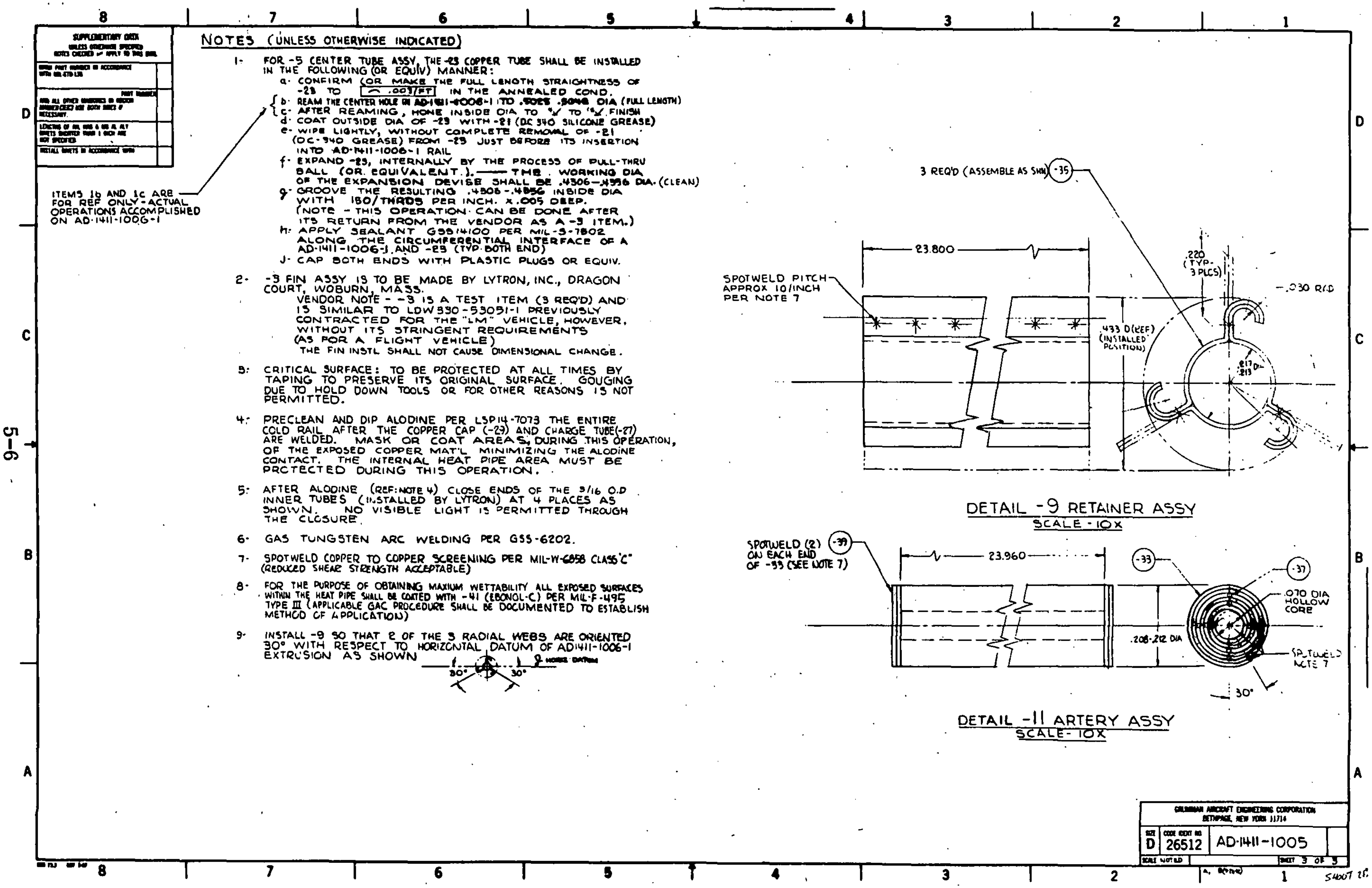


Fig. 5-2 HP Augmented Cold Rail Assembly (Sheet 3 of 3)

The HP uses a spiral artery/tunnel wick to get high capacity and a self-priming capability; the latter being an important feature that eliminates puddle affects and insures valid ground test results. Fine circumferential wall grooves minimize the ΔT across the evaporator and condenser films.

A summary of the HP design details contained in Fig. 5-2 follows:

Envelope

- Material = Copper 101 (OFHC)
- OD = .500 in.
- ID = .433 in.
- Length = 24. in.
- Grooves = circumferential, 150/inch
- Working fluid = Distilled water (charge = 17.5 grams)

Wick

- Material = 100/100 mesh copper screen
- Artery OD = .230 in.
- Tunnel core = .07 in.
- Spiral gap = .010 in.
- Retainer legs = 3

As shown in Figure 5-3, the predicted heat transport capability of the water HP varies from 335 watts to 540 watts over its 70°F to 100°F operating temperature range.

5.2 COMPONENT BENCH TEST RESULTS

Two HP augmented cold rails were built for this program; one to be used for the system test and one to be a life test article. Both cold rails were given preliminary bench tests to evaluate the capabilities of the HP. In addition, the life test cold rail was subjected to vibration loadings equivalent to 100 shuttle missions and then re-checked to determine any performance degradation.

Figure 5-4 shows the instrumentation of a cold rail during bench testing. Twelve copper/constantan thermocouples were used; nine on the cold rail proper, two on the charge tube and one in the spray bath that was used to cool the condenser section.

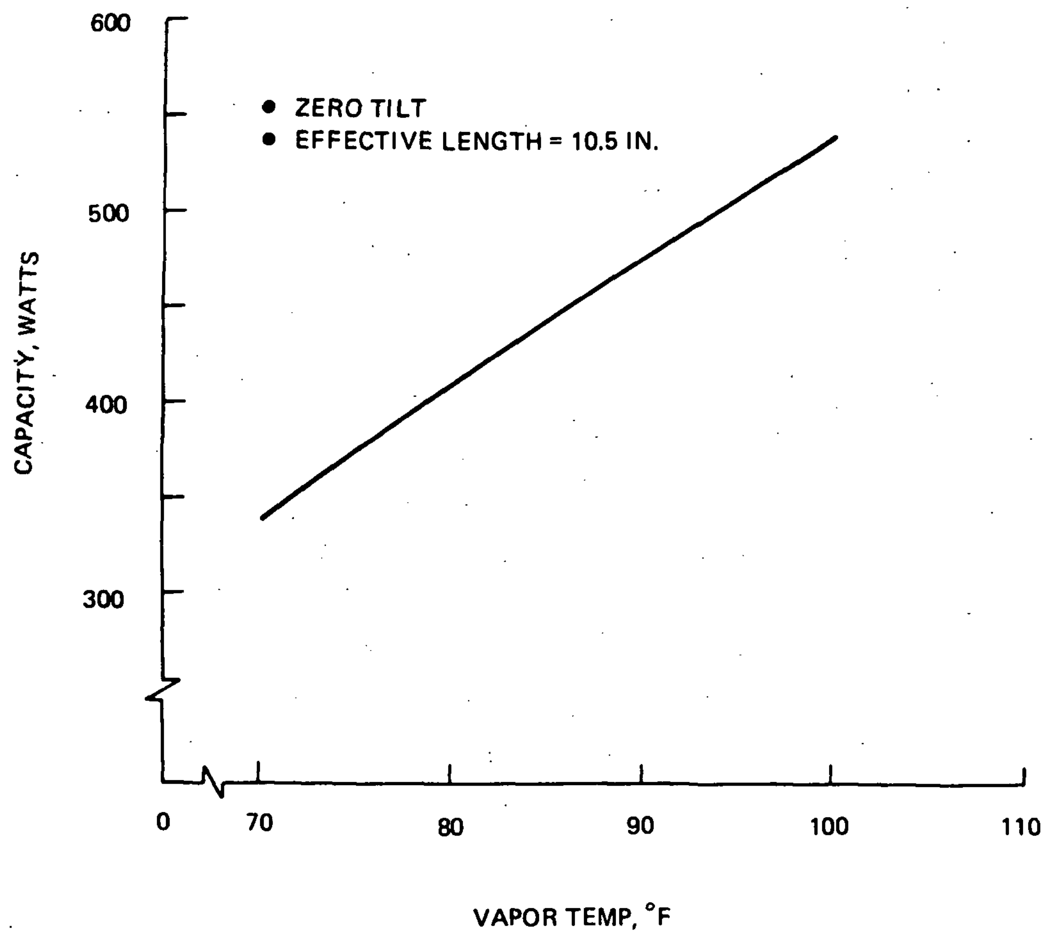
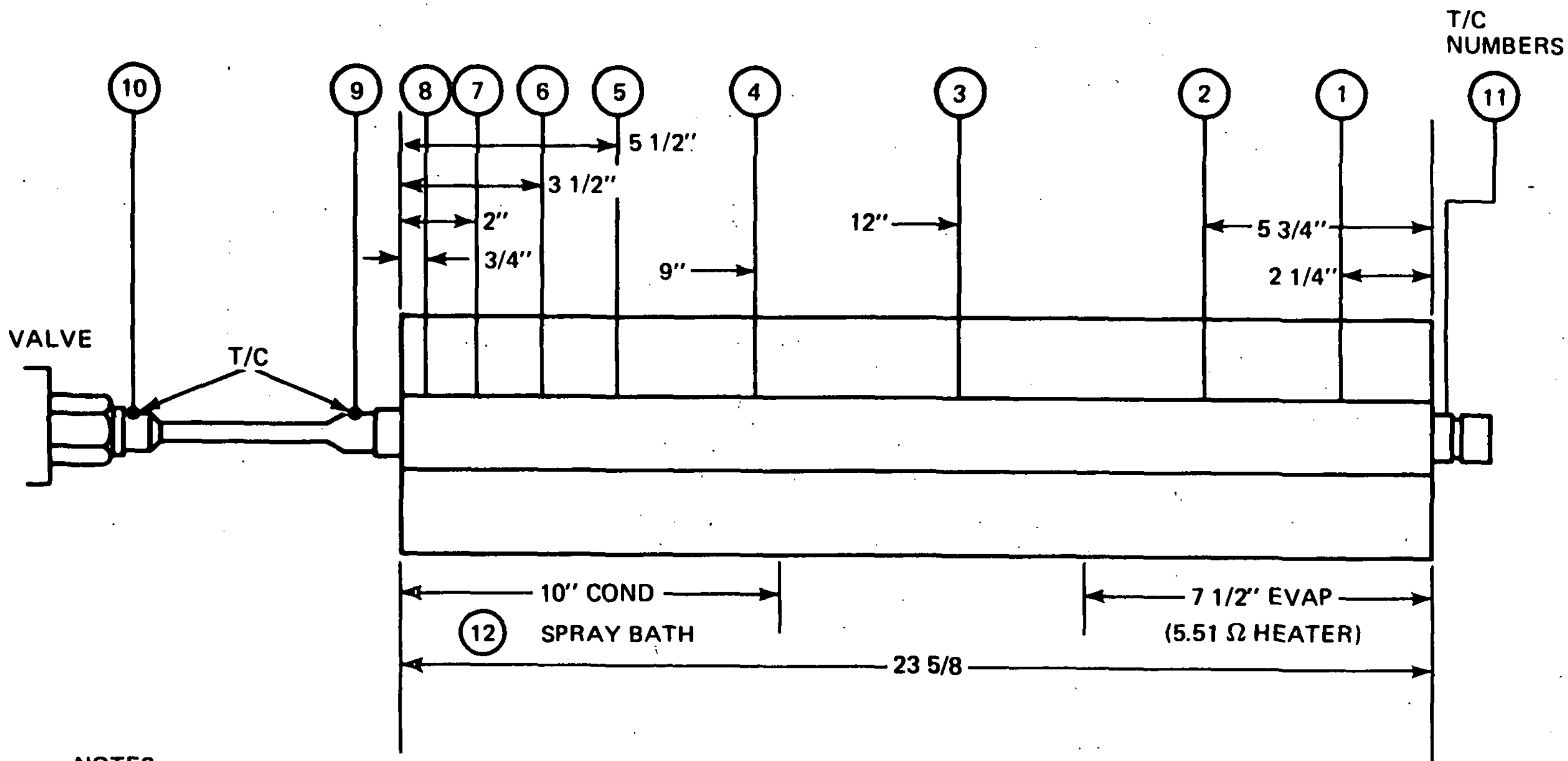


Fig. 5-3 Predicted Water HP Capacity



NOTES:
1) ALL T/C'S ARE CU/CON (30 GAGE)

Fig. 5-4 Instrumentation for HP Augmented Cold Rail Bench Tests

The thermocouples on the rail were placed at the root of the flange as near the HP as possible. Bench test performance was evaluated by operating the cold rail as a normal HP, with an evaporator section on one end and a condenser section on the other. Electrical ribbon heaters were attached to the flanges on either side of the HP on both upper and lower surfaces. A high velocity water spray bath was used for condenser cooling and 1-in. thick Armalfex rubber insulation was used to insulate the rail over the evaporator and transport sections.

Thermocouples 9 and 10 were used as an aid in purging the HP of non-condensible gas after it was initially charged with distilled water. Under load, the readings at these points were equal to the bath temperature if non-condensible gas was present. Burping the pipe, by opening the charge valve to a high vacuum connection, let the gas out. The burping procedure was repeated until the temperatures at 9 and 10 were equal to those in the operating portion of the condenser; an indication that HP action was present throughout the length of the cold rail and that any non-condensible gas was no longer present.

When all of the gas was purged from the HP, the charge tube was pinched tight, checked for leaks, cut and soldered closed. Torr seal, a high vacuum sealant, was used to encase all soldered seals and joints as a precautionary measure. The cold rails were then bench tested at slight adverse tilt.

Figure 5-5 presents the test results for both cold rails and shows the temperature drop between the evaporator flange root and the condenser flange root as a function of heat load, for two sink temperatures. The increased drop at the colder temperatures is due to the increase in condensing vapor temperature drop that occurs at the lower vapor pressures. At a sink temperature of 100°F and a heat load of 300 watts, the temperature drop between the flange roots is 11°F for the life test rail and 7°F for the system test cold rail. The slight difference between results is attributed to small variations in grooving and retainer leg to wall contact that can occur from pipe to pipe.

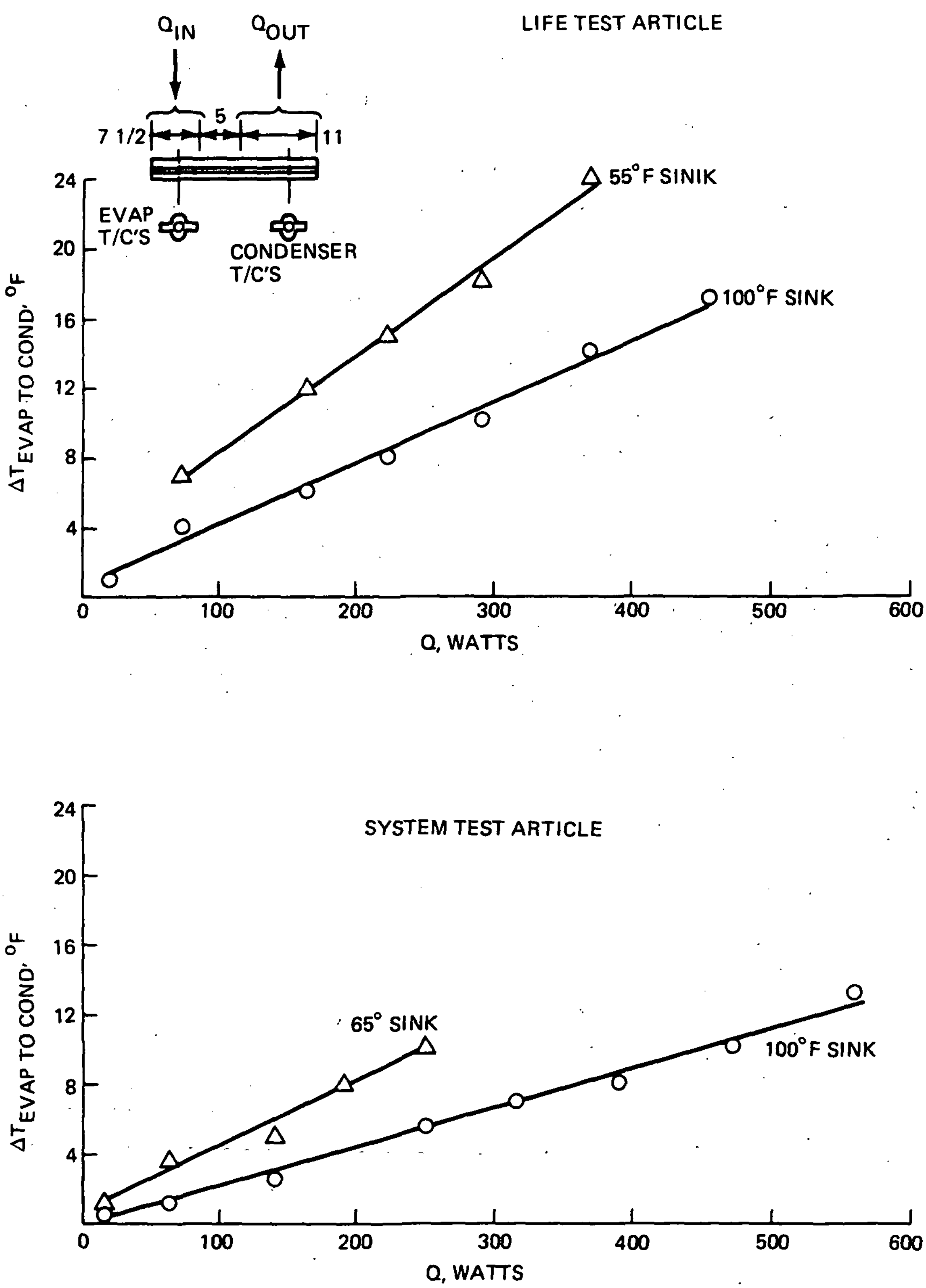


Fig. 5-5 HP Cold Rail Bench Test Data, Before Vibration

After its initial bench test, the life test cold rail was vibration tested (see Appendix A) and then rechecked. Figure 5-6 presents the test results for both the pre- and post-vibration tests. It gives the temperature drop between the evaporator flange root and the condenser flange root as a function of heat load for two sink temperatures. As the data indicates, there has been a slight increase in the ΔT and decrease in the achievable Q_{MAX}. The increased ΔT is attributed to poorer contact between the retainer legs and the pipe wall as a result of the vibration load. These loads also caused slightly enlarged pore radii in the screen artery that resulted in the lower Q_{MAX} values. However, the performance of the HP is still acceptable ($\approx$320 watts at 100°F) in spite of this degradation. Again, the increased temperature drop at the colder 55°F sink temperature is due to the increase in condensing vapor temperature drop that occurs at the lower vapor pressures.

Detailed data sheets for the HP augmented cold rail thermal bench tests are contained in Appendix I.

5.3 SYSTEM TEST RESULTS

Figure 5-7 shows the overall setup for the HP augmented cold rail system tests. Cooling was supplied by a closed-loop fluid conditioning system that used ordinary tap water and provided controllable inlet temperatures and flow rates. The instrumentation diagram for the cold rail is given in Fig. 5-8. Four separate nichrome ribbon heater circuits were used: two for the high power density flanges at either end, and two for the low power density flanges. A total of 36 copper/constantan thermocouples were used to provide readings at the simulated equipment flange roots and the cold rail flange roots. Two of the thermocouples were immersion-type, one at the fluid inlet and the other at the outlet. During the tests, the entire rail assembly was encased in 1 to 2 in. of Armaflex rubber insulation to minimize heat losses. A photograph of the assembled system test article showing the heater circuits and bolted flange connections is given in Fig. 5-9.

The system tests were designed to give the maximum power density capability of the rail as a function of fluid flow rate, inlet temperature and the average loading over the remainder of the rail. Tests were conducted both with and without the HP operating to accurately determine the effects of the HP.

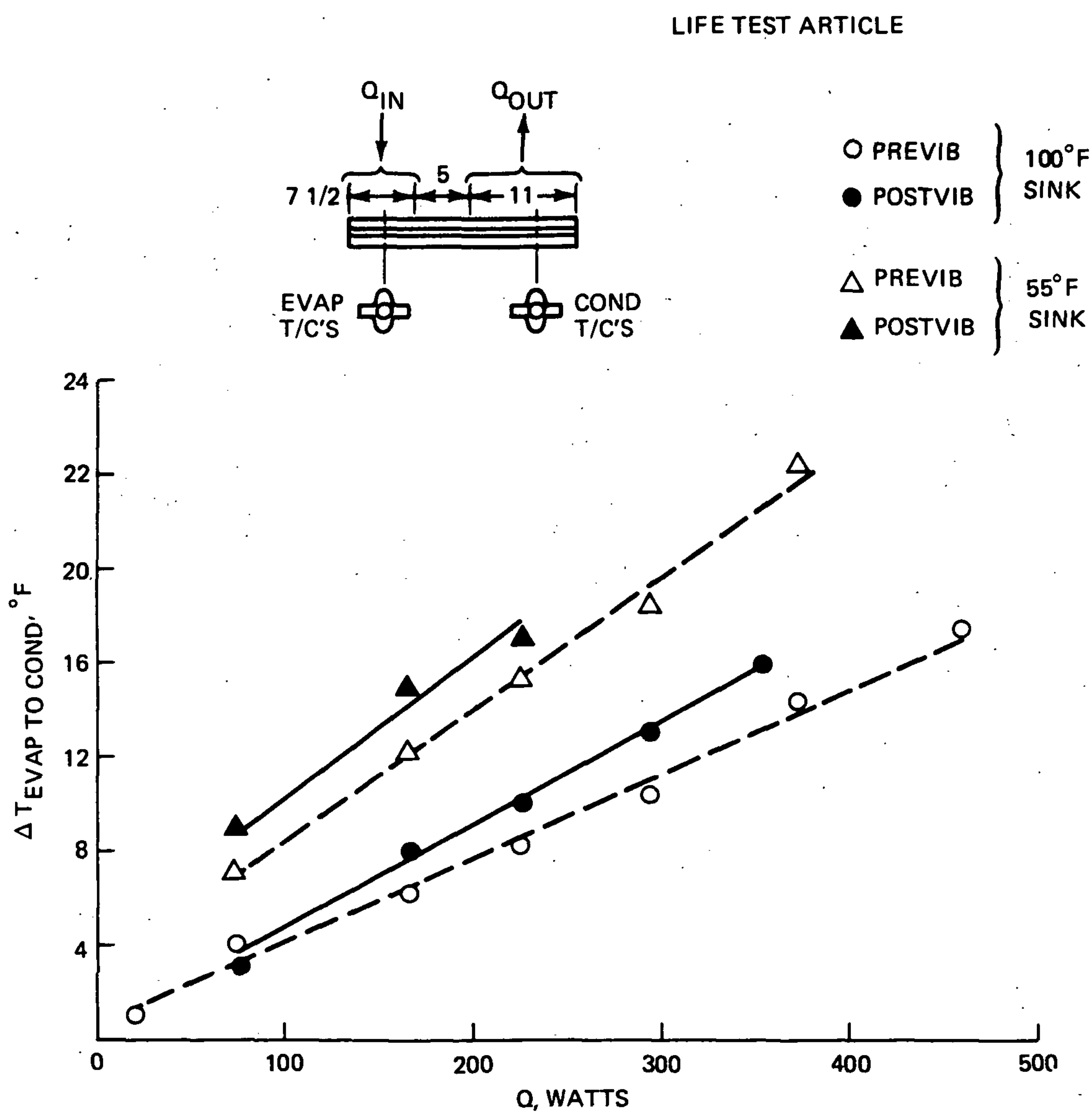


Fig. 5-6 HP Cold Rail Bench Test Data, After Vibration

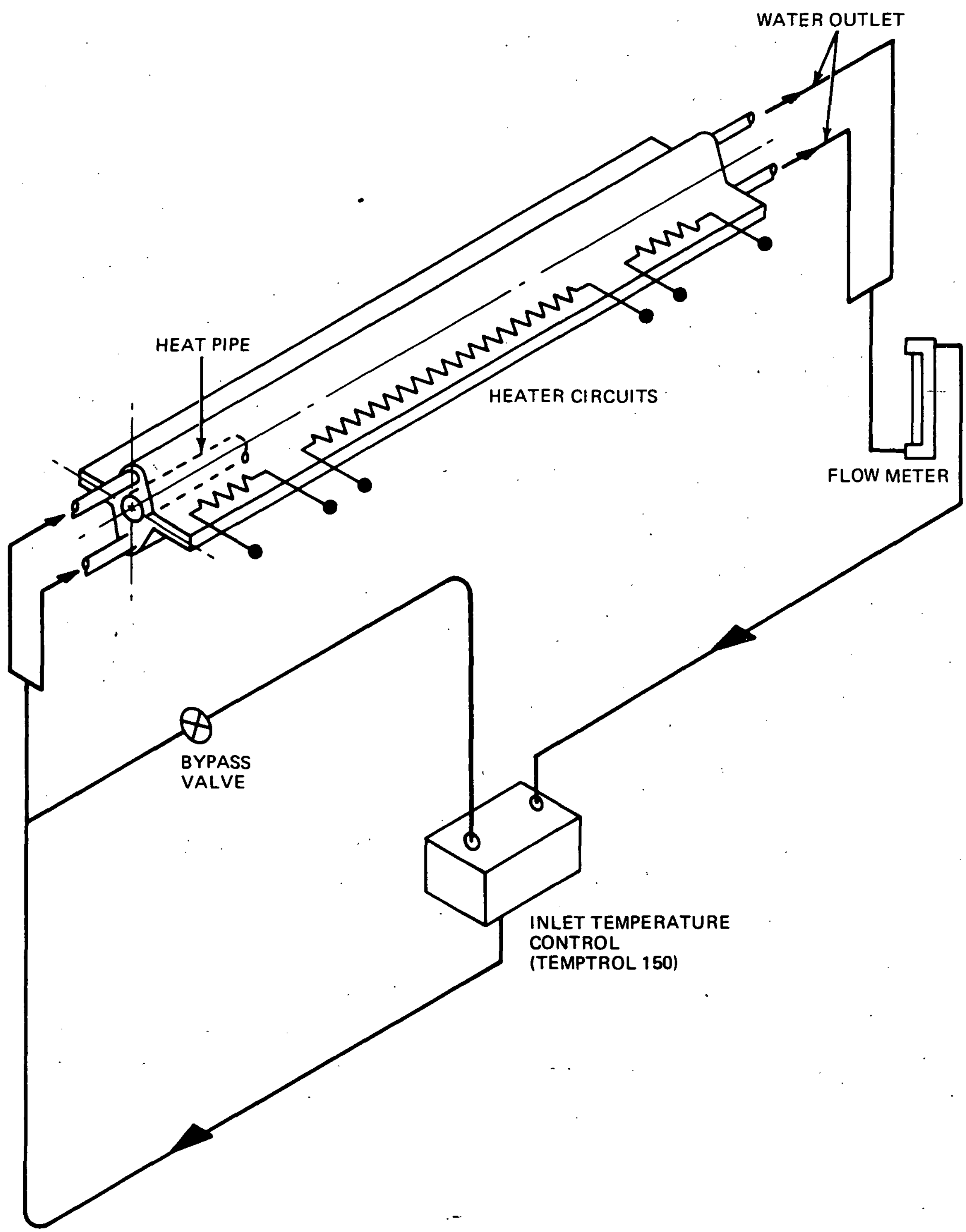


Fig. 5-7 HP Augmented Cold Rail System Test Setup

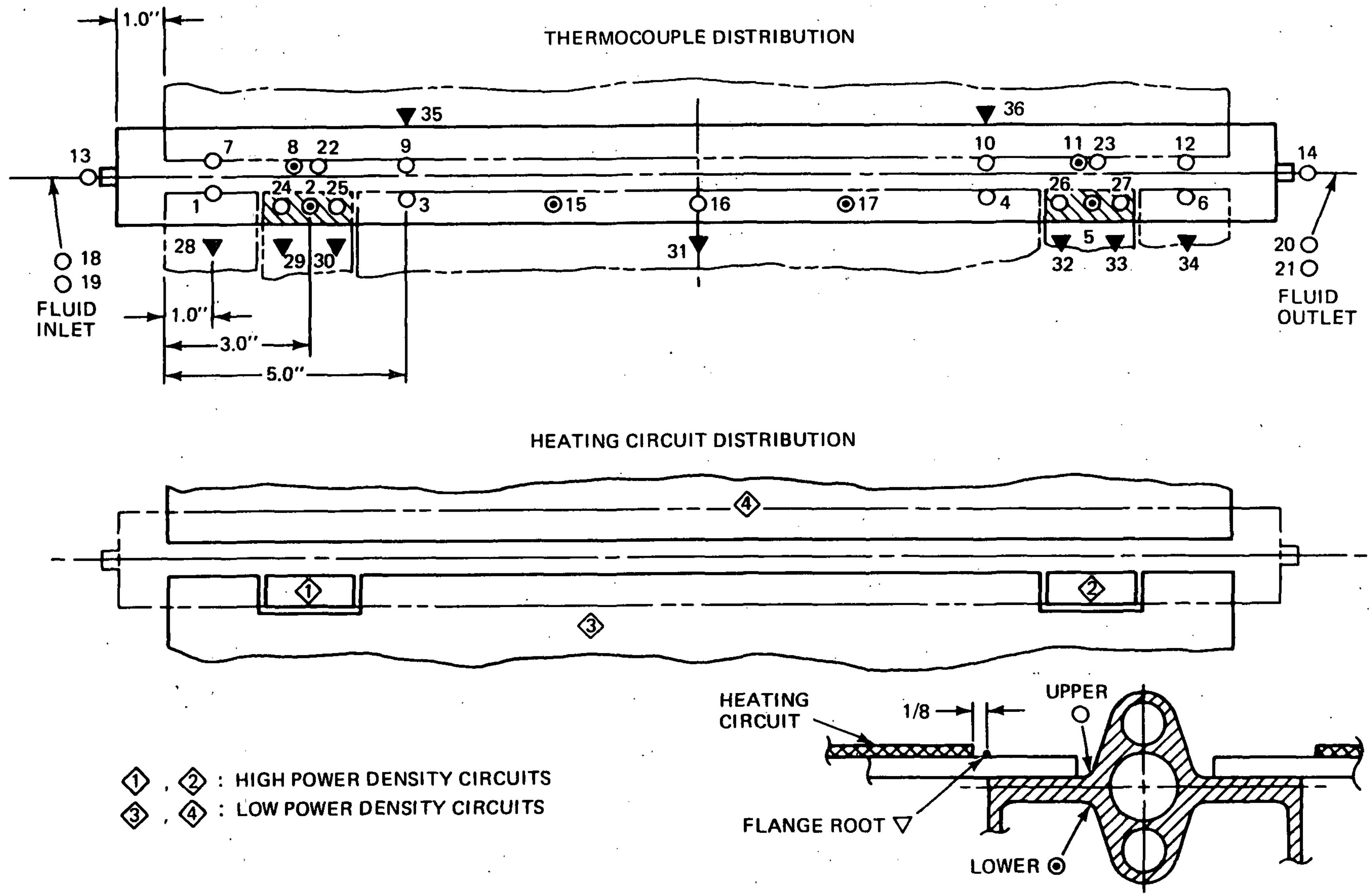


Fig. 5-8 HP Augmented Cold Rail System Test Instrumentation

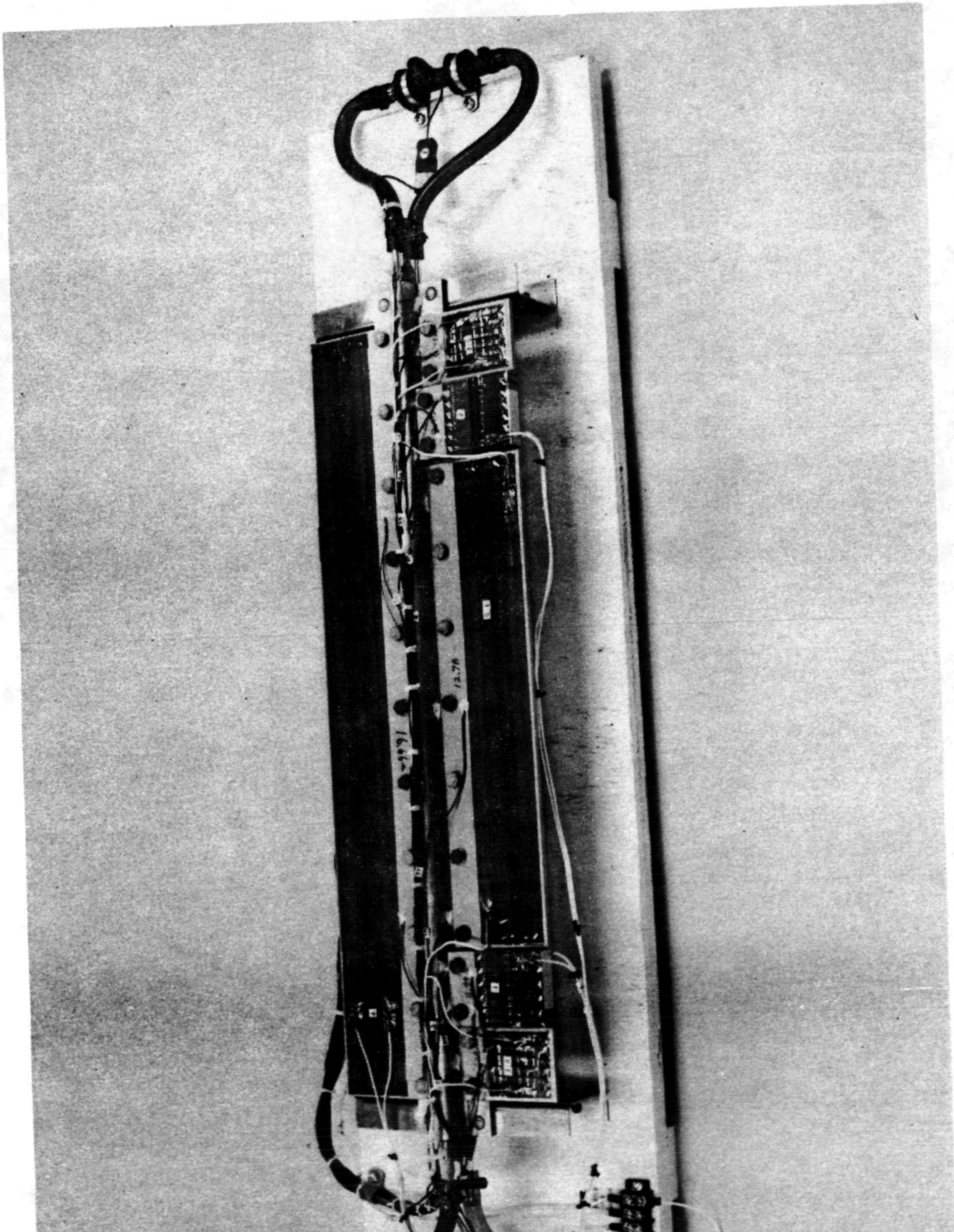


Fig. 5-9 HP Augmented Cold Rail System Test Article

Six basic variables were considered in testing the performance of the HP augmented cold rail:

1. Maximum local load over a 2-inch section of the rail
2. Total equipment load on the cold rail
3. Fluid inlet temperature to the cold rail
4. Fluid flow rate through the cold rail
5. Placement of the high watt-density load
6. Number of operational fluid passages.

The basic pattern consisted of providing a constant input (Q/L_{Low}) to most of the cold rail flange, while one 2-in. section was loaded independently (Q/L_{High}) to simulate a high density electronics package.

Table 5-1 summarizes the test conditions that were run. Tests 1 through 12 and 23 through 26, conducted at varying average loads, local loads, flow rates, and inlet temperatures, were designed to establish the sensitivity of the HP-augmented cold rail to variations in these operating parameters. The tests were performed by fixing all of these parameters except Q/L High, and raising this latter parameter until the HP burned out or until the simulated box flange root reached 140°F (333.2°K). The heat flux which corresponds to the 140°F flange root is indicated by Q* in Table 5-1. Tests 13 through 15 duplicated the conditions of tests 1–3 except that fluid was permitted to flow in only one flow passage to investigate the capabilities of the rail in that failure mode. Tests 16 through 18, conducted with the cold rail mounted vertically and the simulated high watt density equipment location up, demonstrated the capabilities of the cold rail with the heat pipe non-operational. Tests 19 through 22 duplicated the inputs of tests 1 through 4 with the high watt density equipment located at the fluid outlet end of the rail to establish the effect on rail performance of equipment mounting locations.

Pretest predictions of system performance were made by using standard thermal modeling techniques. HP isothermalizing was modeled by defining one HP vapor node as a fixed boundary temperature node during each program iteration, and then redefining its temperature so that it is in thermal equilibrium with the cold rail nodes

TABLE 5-1 RADIATING PANEL SYSTEM TEST CONDITIONS

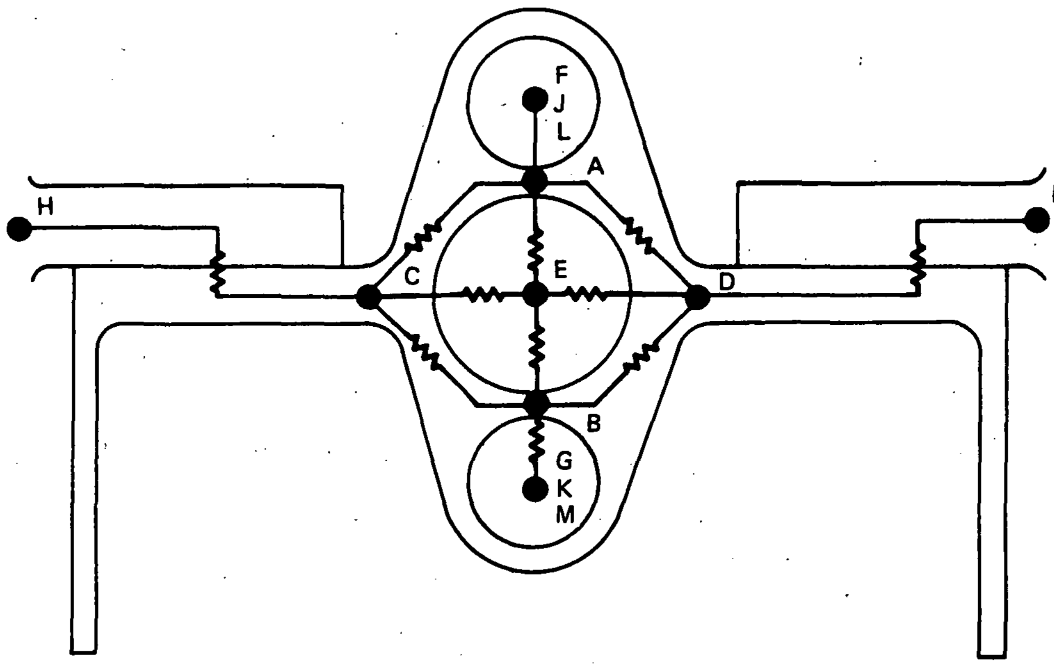
TEST NO.	COOLANT TEMP IN, °F(°K)	COOLANT FLOW LB/HR (KG/HR)	WATTS/IN PER SIDE (WATTS/CM) (Q/L) LOW	WATTS/IN PER SIDE (WATTS/CM) (Q/L) HIGH	COMMENTS
1	70 (294.3)	80 (36.3)	0	0 → burnout	
2			2(5.08)	2 → burnout	
3			4(10.16)	4 → burnout	
4			6(15.24)	6 → burnout	
5	70 (294.3)	40 (18.1)	0	0 → Q*	
6			4(10.16)	4 → Q*	
7	80 (300.0)	80 (36.3)	0	0 → Q*	
8			2(5.08)	2 → Q*	
9			4(10.16)	4 → Q*	
10	90 (305.4)		0	0 → Q*	
11			2(5.08)	2 → Q*	
12			4(10.16)	4 → Q*	
13	70 (294.3)	40 (18.1)	0	0 → Q*	One Passage Operating
14			2(5.08)	2 → Q*	
15			4(10.16)	4 → Q*	
16	70	80 (36.3)	0	0 → Q*	HP Non-Operational Cold Rail Vertical
17			2(5.08)	2 → Q*	
18		40	0	0 → Q*	
19	70	80	0	0 → burnout	High watt density load downstream
20			2(5.08)	2 → Q*	
21			4(10.16)	4 → Q*	
22			6(15.24)	6 → Q*	
23	70	60	0	0 → burnout	
24			2	2 → burnout	
25			4	4 → burnout	
26			6	6 → burnout	

in contact with it. The appropriate conductance for evaporation or condensation is used, depending on whether the wall temperature subsequent to the last iteration was higher or lower than the HP vapor temperature. The model for a typical rail section is shown in Fig. 5-10: 12 such sections were used to model the entire rail.

Table 5-2 summarizes the results for the test conditions and lists predicted heat loads and flange temperatures corresponding to a 140°F maximum temperature at the high watt density location. These predictions reflect the following nominal system parameters:

Parameter	Nominal Value (BTU/hr ft^2°F)
$h_{interface}$	1000
$h_{evaporator}$	2000
$h_{condenser}$	2500
$h_{flow\ passage}$	206 (Based on passage ID)

System test results are summarized in Fig. 5-11 through 5-16. Figure 5-11 shows the variation in the simulated equipment flange root temperatures with power dissipation and inlet temperature for the 80 lb/hr water flow rate. As expected, behavior is linear. From Fig. 5-11 (a), at a 70°F inlet temperature, it can be seen that a flange root temperature of 140°F can be maintained with power dissipations as high as 45 watts/in. (over 2 in.) on the high-power flange and 6 watts/in. on the low-power flanges. With no input to the low-power flanges and a 70°F inlet, a high-power density of 50 watts/in. (over 2 in.) and a 136°F flange root temperature was achieved. The higher inlet temperatures (e.g., 80°F and 90°F) result in proportionately lower permissible high-power inputs, while maintaining the 140°F maximum equipment flange temperature constraint. There is also a proportionate increase in the HP vapor temperature with the higher inlet temperatures. Referring to Fig. 5-11 (c), the inlet temperature has by far the strongest influence on the vapor temperature. The increase in vapor temperature due to increase in the high-power and low-power inputs is small; less than 3°F at most. At the low-power flanges, Fig. 5-11 (b), the flange temperature is only slightly affected by increases at the high-power location.



NODE	DESCRIPTION/LOCATION
A	BETWEEN HP AND FLUID PASSAGE
B	BETWEEN HP AND FLUID PASSAGE
C	AT COLD RAIL MOUNTING FLANGE ROOT
D	AT COLD RAIL MOUNTING FLANGE ROOT
E	HP VAPOR TEMP
F	FLUID "INLET" TEMP
G	FLUID "INLET" TEMP
H	MODULE BOX FLANGE ROOT TEMP
I	MODULE BOX FLANGE ROOT TEMP
J	FLUID PASSAGE OUTLET TEMP
K	FLUID PASSAGE OUTLET TEMP
L	FLUID "MEAN" TEMP
M	FLUID "MEAN" TEMP

Fig. 5-10 Typical Section of Cold Rail Thermal Model

TABLE 5-2 PREDICTED PANEL TEMPERATURES

TEST NO.	T_{INLET}, °F	$T_{HI\text{-}LOAD}$ MODULE FLANGE ROOT	M, $\frac{lb}{hr}$	Q_{LO}, WATTS	Q_{MI}, WATTS	T_{HP} °F	T_{HP} °K	T_{OUTLET} °F	T_{OUTLET} °K	$T_{RAIL\ FLANGE}$ ROOT (HI-LOAD) °F	$T_{RAIL\ FLANGE}$ ROOT (HI-LOAD) °K	$T_{LO\text{-}LOAD\ MODULE}$ FLANGE ROOT °F	$T_{LO\text{-}LOAD\ MODULE}$ FLANGE ROOT °K	$T_{RAIL\ FLANGE}$ ROOT (LO-LOAD) °F	$T_{RAIL\ FLANGE}$ ROOT (LO-LOAD) °K
1	70	140	80	0	80.5	77.8	298.6	73.4	296.2	90.8	305.9	77.5	298.5	77.5	298.5
2	70	140	80	2	72.0	84.9	302.6	76.6	298.0	96.3	308.9	91.5	306.2	85.2	302.7
3	70	140	80	4	63.2	92.1	306.6	79.7	299.7	101.6	311.9	105.7	314.1	92.8	307.0
4	70	140	80	6	54.4	99.1	310.5	82.8	301.4	106.7	314.7	119.6	321.9	100.3	311.1
5	70	140	40	0	76.3	81.2	300.5	76.5	297.9	93.5	307.3	80.8	300.3	80.8	300.3
6	70	140	40	4	51.4	101.1	311.6	88.1	304.3	108.7	315.8	114.9	319.2	101.9	312.0
7	80	140	80	0	69.2	86.6	303.5	82.9	301.4	97.9	309.8	86.4	303.4	86.4	303.4
8	80	140	80	2	60.4	93.8	307.5	86.1	303.2	103.3	312.8	100.4	311.2	94.0	307.6
9	80	140	80	4	51.6	100.9	311.4	89.2	304.9	108.7	315.8	114.7	319.1	101.7	311.9
10	90	140	80	0	57.7	95.6	308.5	92.4	306.7	104.9	313.7	95.3	308.3	95.3	308.3
11	90	140	80	2	49.0	102.7	312.4	95.6	308.5	110.3	316.7	109.4	316.2	102.9	312.6
12	90	140	80	4	40.0	109.8	316.4	98.7	310.2	115.7	319.7	123.6	324.1	110.7	316.9
13	70	140	40	0	73.3	83.2	301.6	75.8	297.5	95.4	308.4	82.9	301.4	82.9	301.4
14	70	140	40	2	58.5	95.0	308.2	80.9	300.3	104.7	313.6	101.7	311.9	95.5	308.4
15	70	140	40	4	43.7	107.0	314.8	86.1	303.2	113.7	318.6	120.7	322.4	107.8	315.3
16	70	140	80	0	58.1	–	–	72.2	295.5	104.5	313.4	72.6	295.7	72.6	295.7
17	70	140	80	2	53.9	–	–	75.8	297.5	107.3	315.0	87.8	304.2	81.6	300.7
18	70	140	40	0	53.5	–	–	74.6	296.8	107.2	314.9	74.8	296.9	74.8	296.9
19	70	140	80	0	80.6	77.6	298.5	73.4	296.2	90.9	305.9	77.4	298.4	77.4	298.4
20	70	140	80	2	71.6	84.8	302.5	76.6	297.9	96.4	308.9	91.4	306.2	85.0	302.6
21	70	140	80	4	62.7	91.9	306.4	79.7	299.7	102.0	312.1	105.5	314.0	92.6	306.8
22	70	140	80	6	53.7	99.0	310.4	82.8	301.4	107.5	315.1	119.6	321.8	100.1	311.0
T/C NO.	18,19	29,30 (32,33)*				13,14		20,21		2, 24, 25 (5, 26, 27)*		28, 31, 34, 35, 36		1, 3, 4, 6-12, 15-17, 22, 23	

* T/C numbers for tests 19-22 only.

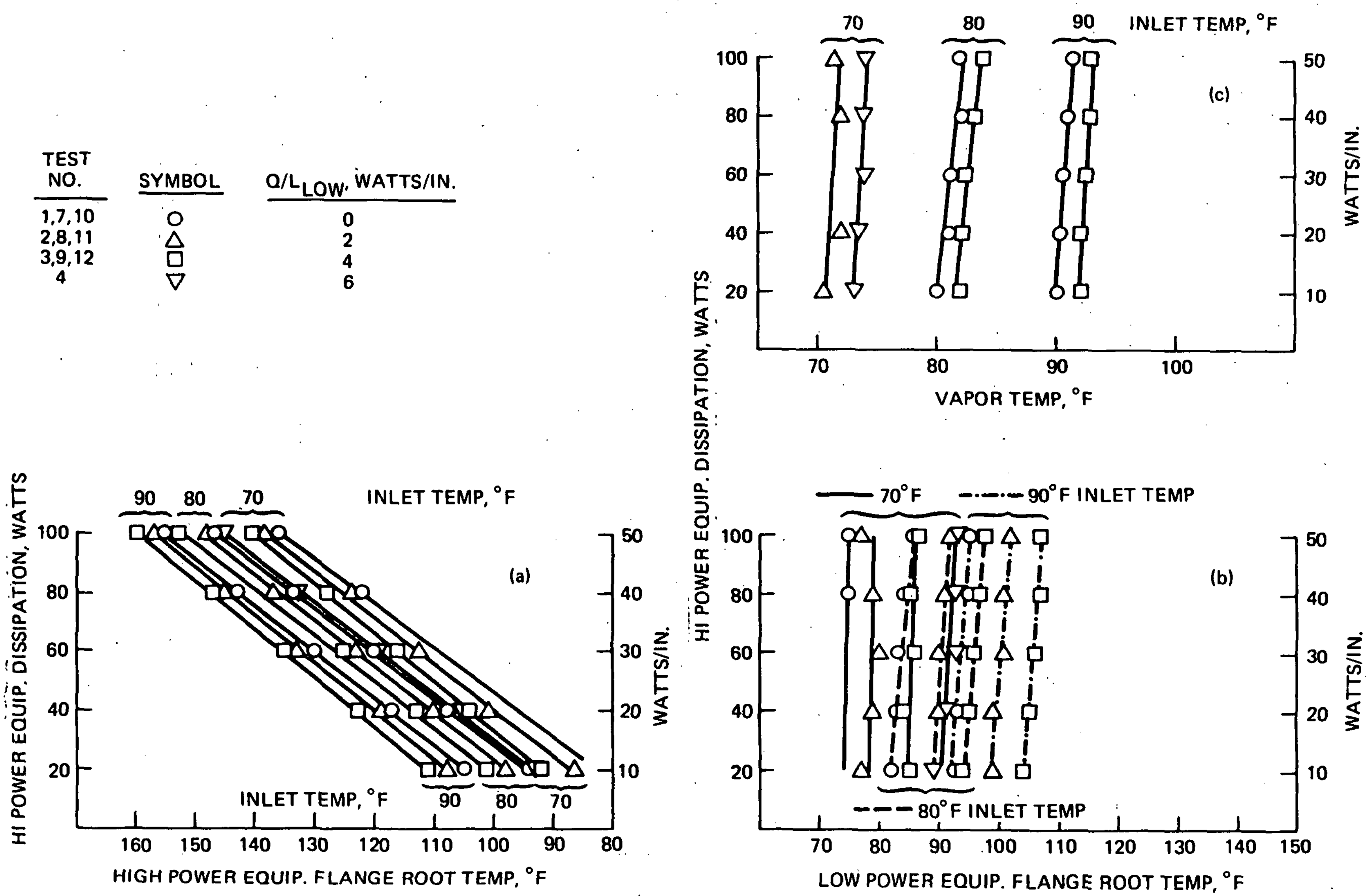


Fig. 5-11 HP Augmented Cold Rail System Test Data, Flow = 80 Lb/Hr, Variable T_{Inlet}

TEST NO.	SYMBOL	Q/L_{LOW}, WATTS/IN.	FLOW RATE, LB/HR
5	○	0	40
1	●	0	80
6	□	4	40
3	■	4	80

P = PREDICTED POINTS (SEE TABLE 5-2)

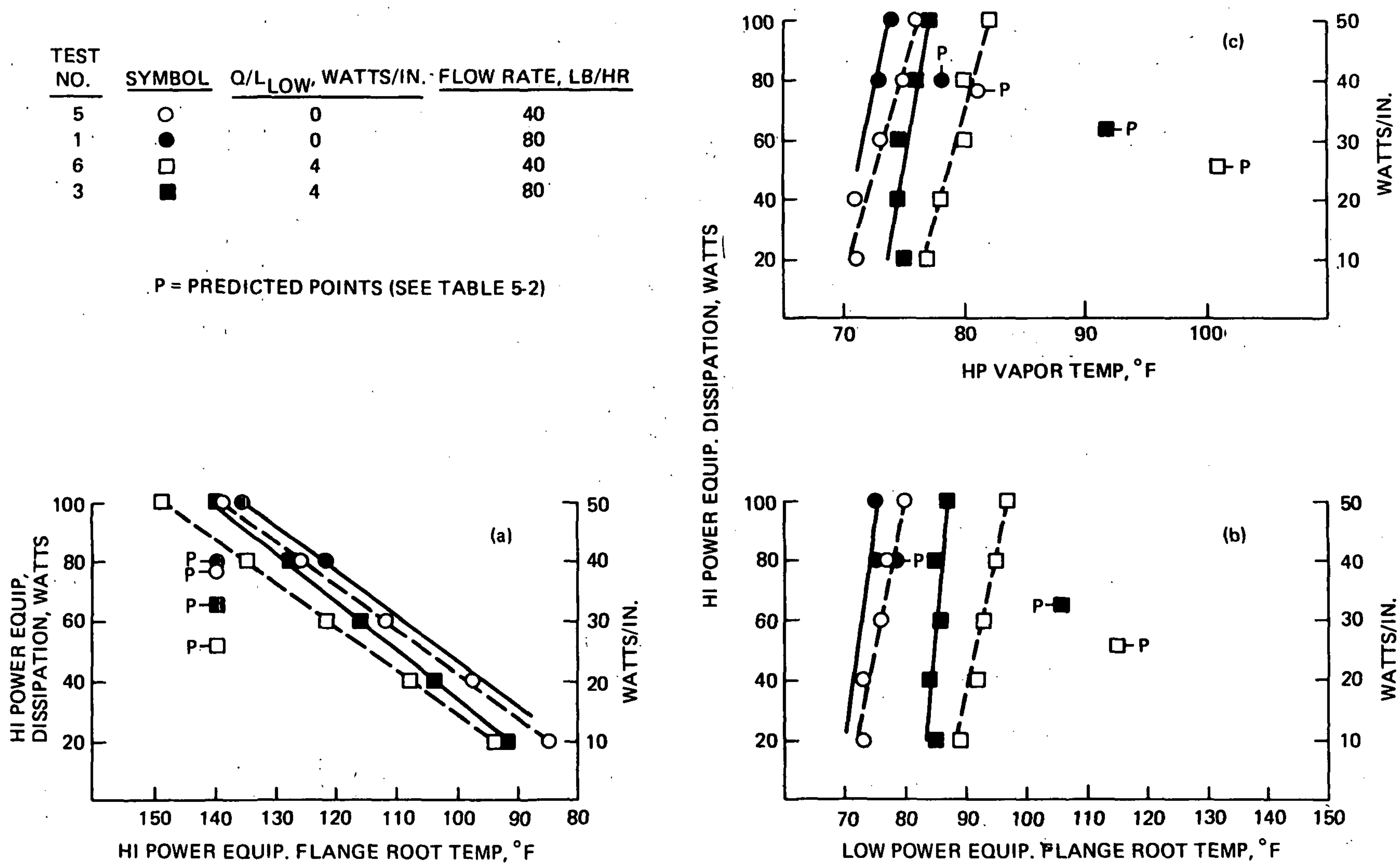


Fig. 5-12 HP Augmented Cold Rail System Test Data, Variable Flow, $T_{Inlet} = 70^{o}F$

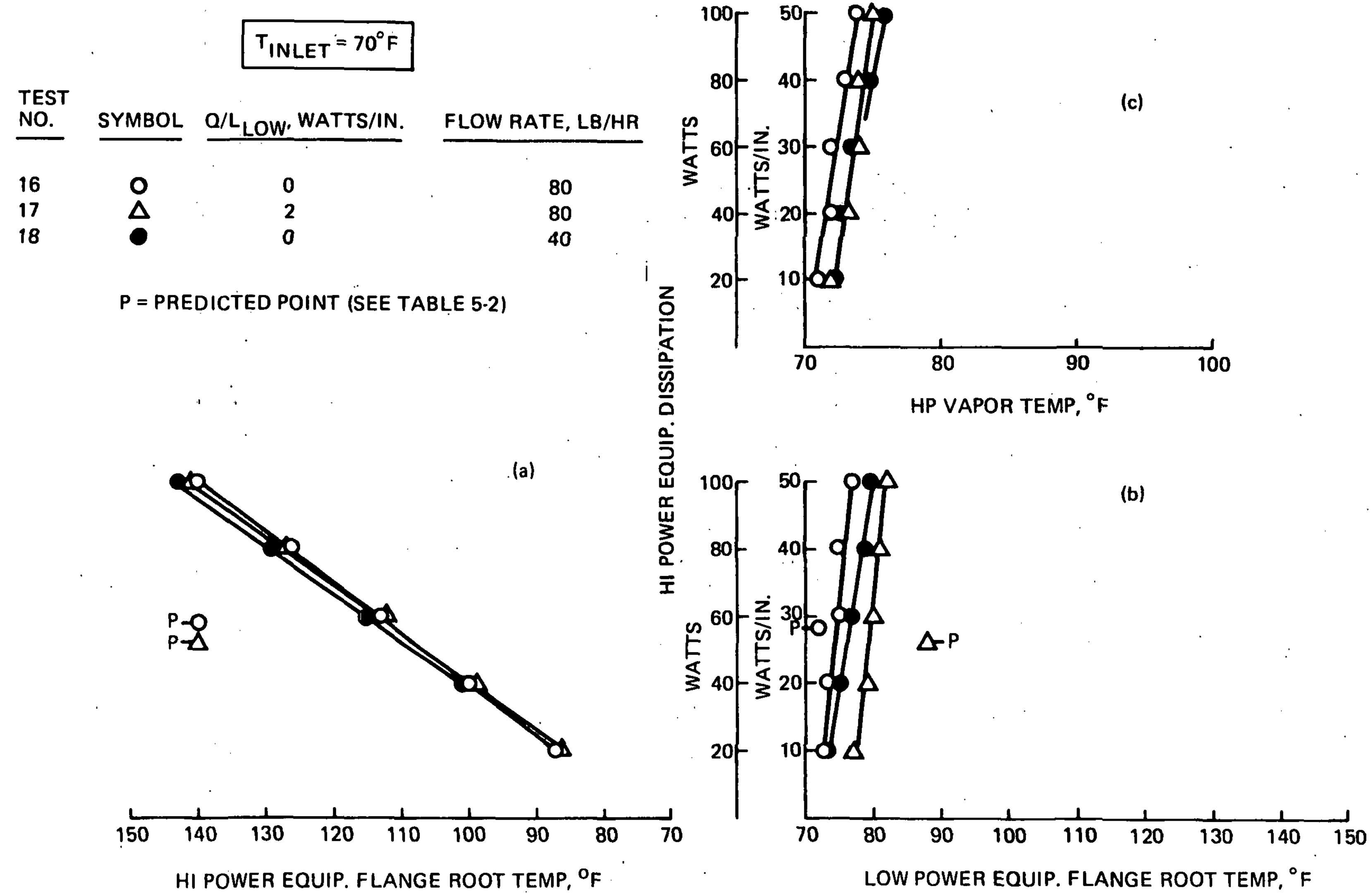


Fig. 5-13 HP Augmented Cold Rail System Test Data, HP Non-Operational

T_{INLET} = 70°F, FLOW RATE = 80 LB/HR

HIGH Q LOC	SYMBOL	TEST NAME	TEST NO.	Q_{HI}, W	Q/L, W/IN.
ON INLET	△ ○	HEATER PLATE HEAT PIPE	1	100	0
	△ ○	HEATER PLATE HEAT PIPE	4	100	6
ON OUTLET	▲ ●	HEATER PLATE HEAT PIPE	19	100	0
	▲ ●	HEATER PLATE HEAT PIPE	22	100	6

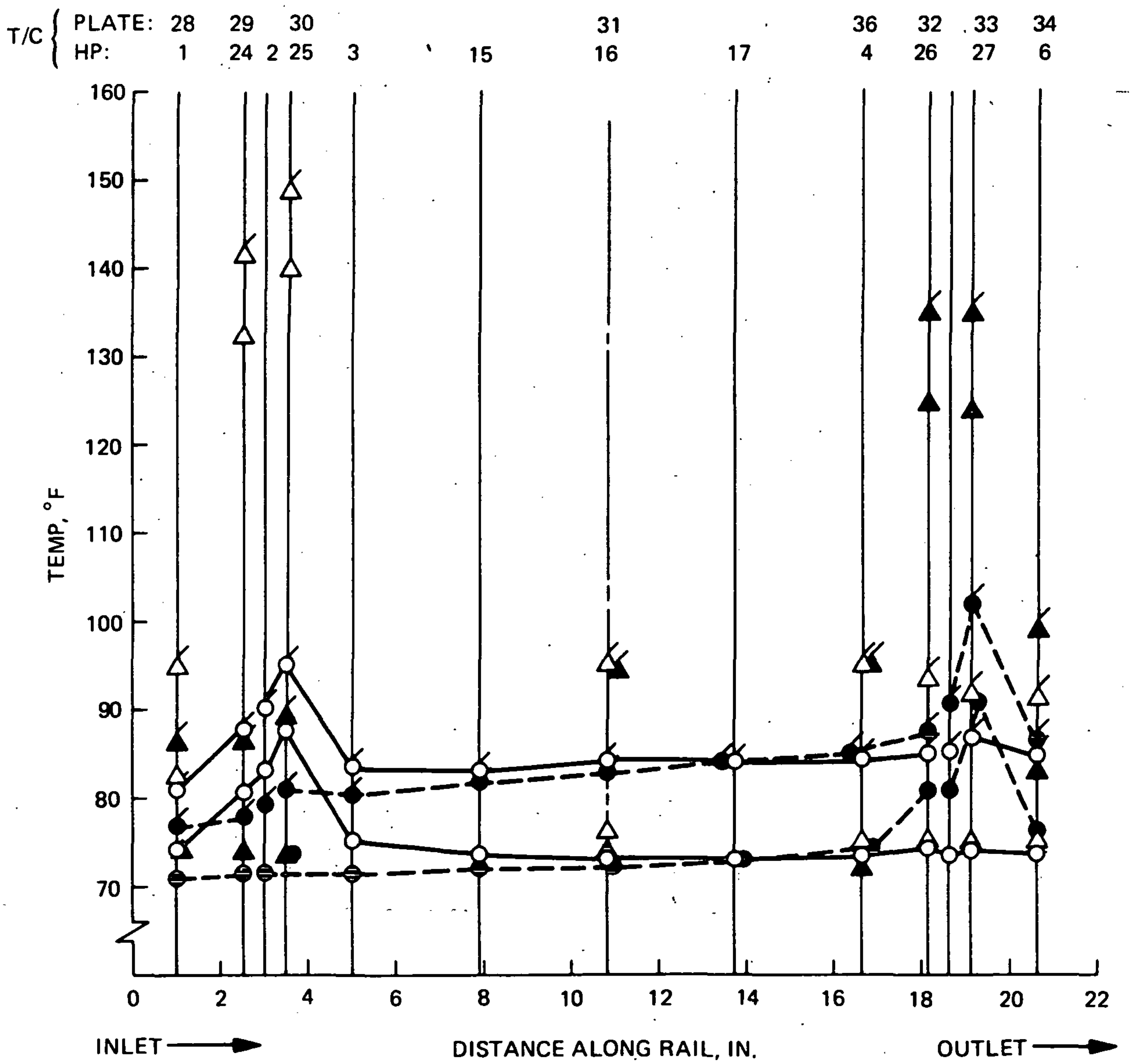


Fig. 5-14 HP Augmented Cold Rail System Test Temperature Profiles

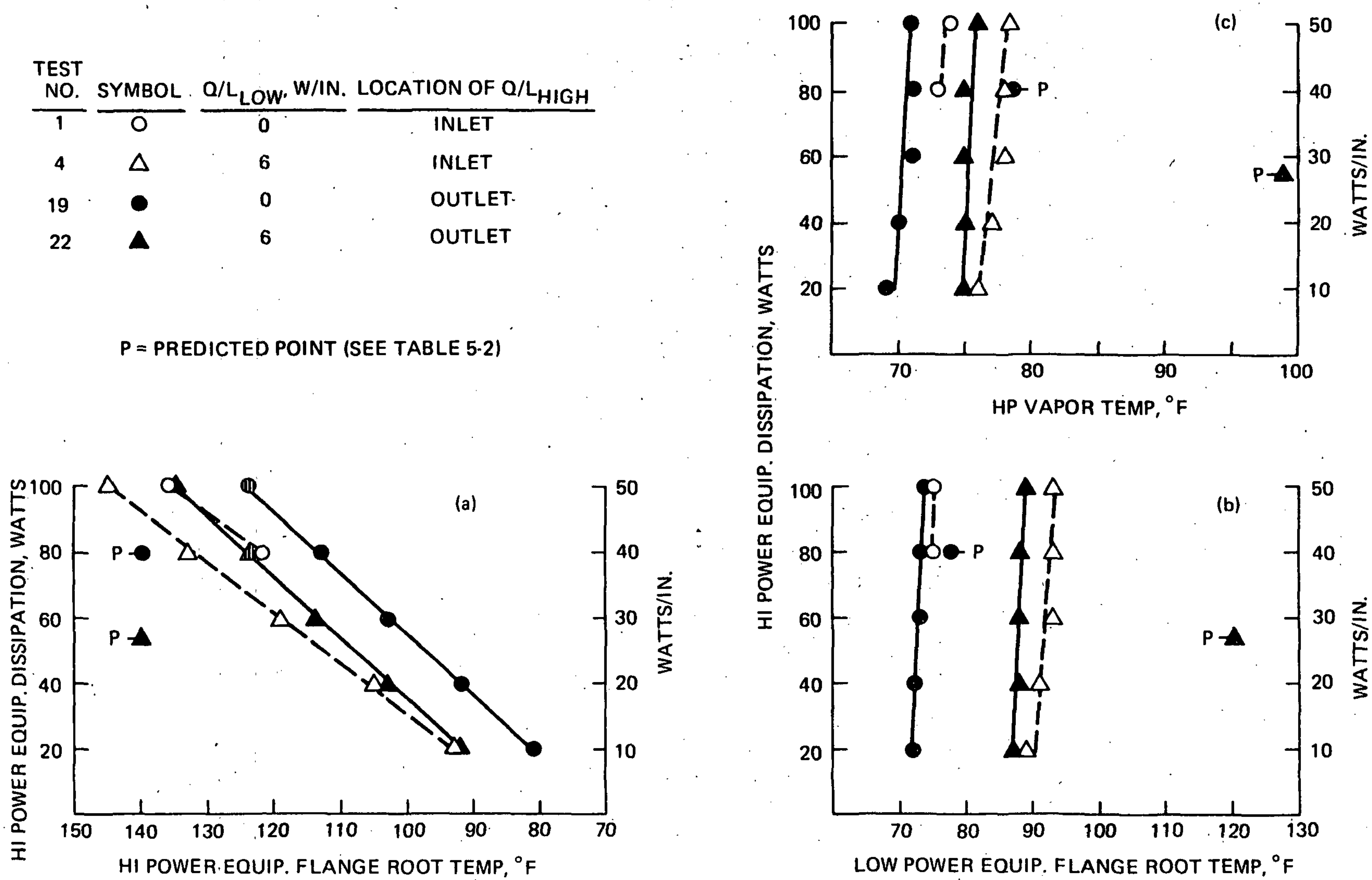


Fig. 5-15 HP Augmented Cold Rail System Test Data, $T_{Inlet} = 70^{o}F$, Flow = 80 Lb/Hr

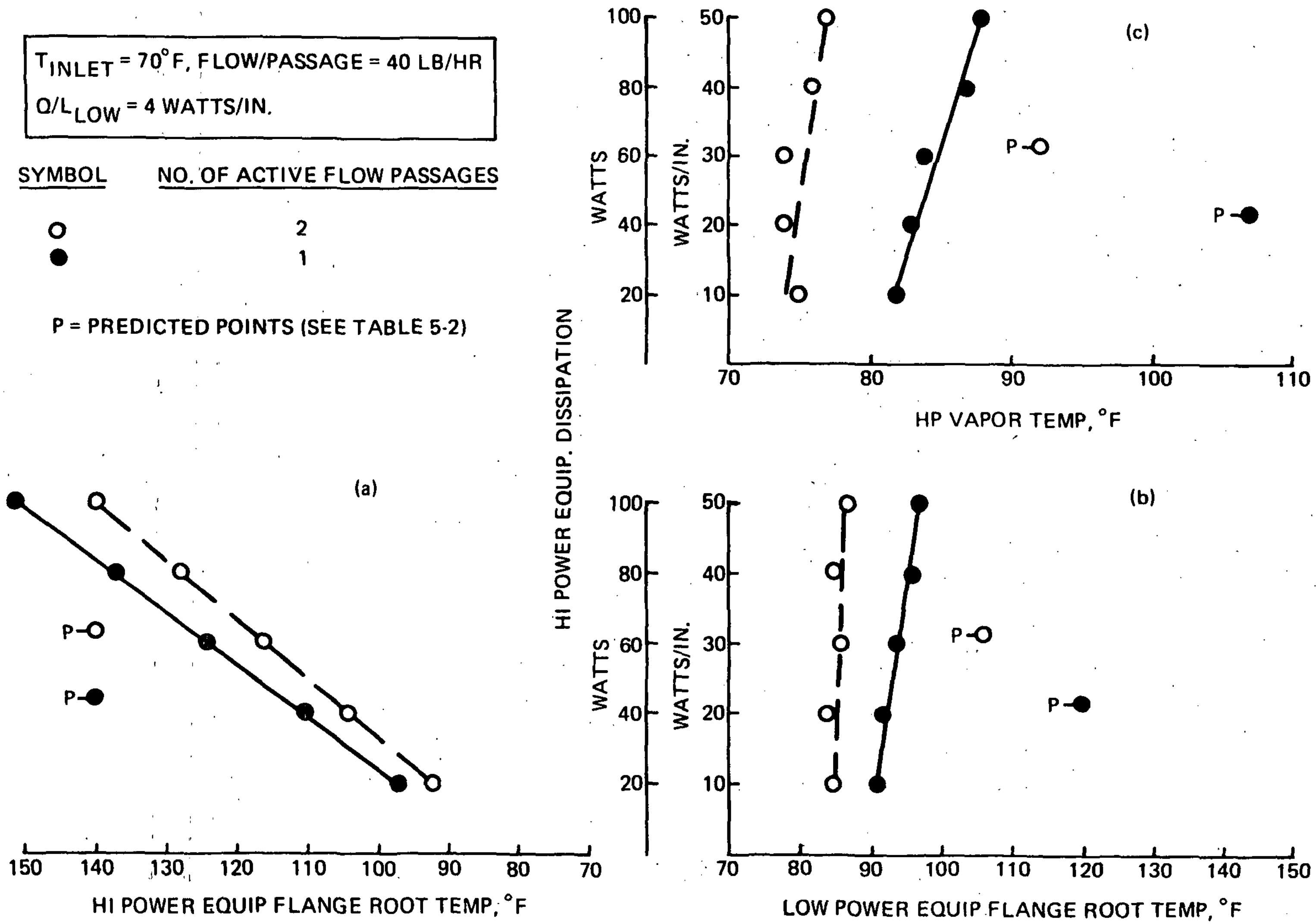


Fig. 5-16 HP Augmented Cold Rail System Test Data, Varied Flow Passages

Cold rail performance as a function of flow rate is given in Fig. 5-12 for the baseline 70°F inlet temperature. Halving the flow rate, from 80 to 40 lb/hr, decreases the permissible high power input by less than 15%, at worst. The decrease is most pronounced as the load to the low-power flanges is increased. Predicted performance points are also indicated on the figure and show lower high-power inputs (for a 140°F max flange temperature) than were actually demonstrated during the tests. They also predict higher vapor temperatures which supports the hypothesis that the direct heat transfer coupling between the heat source and the fluid passage is greater than what was calculated. As a matter of fact, for a 40-watt/in. input, increasing the contact conductance between the rail and equipment plate flanges and the fluid passage heat transfer film coefficient by 50%, results in a predicted decrease of 16°F at the high power flange root (from 140°F to 124°F), which is close to the actual performance.

Figure 5-13 presents the test results with the HP rendered non-operational. The cold rail was held vertically and heat inputted at the top end. For the 80 lb/hr flow rate and zero heat input to the low-power flanges, 100 watts were inputted to the high-power flange before a root temperature of 140°F was achieved. This compares with a root temperature of 136°F measured with the cold rail level and HP operating. The small 4°F difference is attributed to the much stronger than anticipated direct thermal coupling between heat source and fluid. This coupling had the effect of short circuiting most of the heat before it could enter the HP. When the rail was operated with a spray bath at the lower end instead of water flowing through the passages, it quickly burned out as demonstrated by runaway heater flange temperatures. After it was leveled, it behaved as a normal HP and transferred the applied heat load.

The effect of reversing the location of the high power density load from inlet side to outlet side is shown in Fig. 5-14 and 5-15. Although the analysis predicts no difference in temperatures, the test results show slightly lower temperatures with the high-power load on the outlet side (See Fig. 5-14). This is contrary to what one might expect and can only be explained by a variation in contact conductance between these locations. The conductance between the high-power flange and the rail is greater at

the outlet side, possibly due to variations in surface condition and bolt torque. The difference between corresponding temperatures at the HP locations (o,●) is much smaller than the difference at the heater plate locations (△,▲). It is about 3°F for the former and about 12°F for the latter.

The effect of changing the number of active flow passages from two to one is seen in Fig. 5-16. The bottom flow passage was capped shut on both the inlet and outlet sides. Performance at the high-power flange (at 140°F) has been degraded by about 8 watts/in., from 50 to 42, by using only one passage. This is close to the 9.5 watt/in. reduction that was predicted. The HP vapor temperatures were much higher (see Fig. 5-16 (c)) because more of the heat was being diverted into the HP; what would have gone into the lower flow passage went into the HP.

The detailed data sheets for the HP augmented cold rail system tests are contained in Appendix J.

Section 6

CONCLUSIONS

The significant conclusions that can be drawn from this program are as follows:

- HP thermal control systems are feasible for selective applications on the space shuttle as a supplement to baseline systems.
- The HP radiating panel is applicable to any isolated compartment that contains a convenient fluid waste heat source. It can be used to supplement the baseline systems for on-orbit temperature control with minimum impact on the existing fluid subsystems. The convenience of the strap-on concept also makes its use feasible at most any time in the design cycle.
- The simple strap-on coupling can extract reasonable amounts of energy ($\approx$6 watts/ft^2 of radiating surface) from existing fluid lines without internal or extensive external line modifications.
- The modular heat sink concept is valid for use with remote power dissipating sources. A HP coupling to a structural or PCM sink can now be considered as a solution to thermal control problems that arise well after subsystem design freezes.
- HPs can operate in a reflux mode when subjected to a 3-g inertial force.
- HPs can be used to augment fluid cold rails but their beneficial affect on performance is strongly dependent on cold rail design and may be small. The ralative worth of their use would depend on the requirements of the specific application.
- The effect of 100-shuttle-mission vibration loadings on the performance of the artery HPs is not severe and in two out of three cases was minimal. A design safety factor of two should be more than enough to compensate for any uncertainties in future applications.

Section 7

RECOMMENDATIONS

The feasibility of using selected HP thermal control systems for the space shuttle has been established by this program. But there are additional steps that must be taken before any of them can be implemented as flight hardware.

Specific flight-weight prototype versions must be built and tested that precisely reflect up-to-date system needs, particularly interface requirements and geometric constraints. This is especially true for the application of HP radiating panels for compartment temperature control. They must be designed to conform to the actual compartment geometry and fluid line installations.

Considering the fine performance of the HP panel, using them in conjunction with the integrated thermal control system concept is worthy of a much closer evaluation by shuttle management.

Section 8

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Appendix A

VIBRATION TESTS

A representative HP from each of the three HP systems was subjected to shuttle mission-level vibration loads to demonstrate the survivability of the wicking structure and HP envelope. The selections consisted of the diode HP from the modular heat sink system, feeder pipe 01 from the radiating panel, and one of the augmented cold rails.

Vibration levels were formulated for three internal regions of the shuttle (619 configuration) where the respective HPs would be located: cabin (augmented cold rail), payload (feeder pipe), and aft fuselage (diode). These are internal regions, that is, the HPs are not fastened directly to structure subject to direct impingement of external acoustic excitation but are fastened to structure excited by internal acoustic energy which is transmitted through the outer hulls or walls. The external acoustic levels were derived for rocket engine firing during launch and boost and the corresponding internal levels were calculated from the shuttle orbiter transmission characteristics and internal absorption characteristics in each of the three regions. Only gross structural features were accounted for and the effects of mass loading or the presence of particular pieces of equipment were not included. Excitations occurring during other mission phases such as transonic and supersonic flight, entry and horizontal flight were ignored since they were well below those occurring during launch and boost.

The resulting random vibration power spectral density curves are plotted in Fig. A-1. The diode HP and the radiator panel feeder HP were tested at the levels indicated by the maximum composite profile; the cold rail was tested at the indicated cabin levels. Due to the symmetry in the circular cross section of the HPs, they were only vibrated along two mutually perpendicular axes; the longitudinal axis and one radial axis. The total test time per axis was 66.67 minutes, the equivalent of 100 shuttle missions.

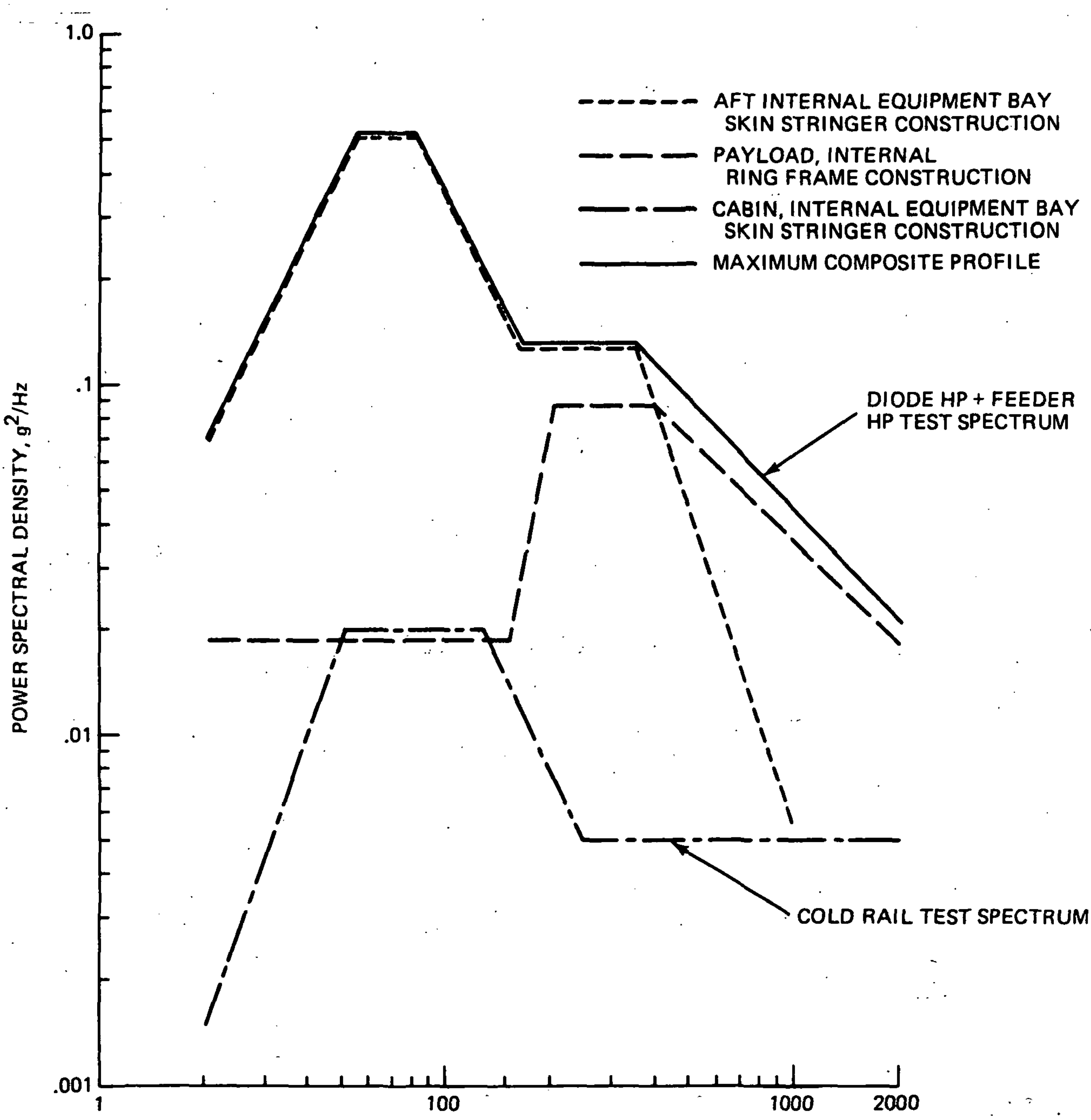

Figure A-1 Space Shuttle 619 Configuration Vibration Levels During Launch & Boost

Appendix B

PCM CANISTER DESIGN

Figures B-1 and B-2 give the calculated values of effective conductance and weight, per inch of canister length, as a function of the fins per inch. They were used to determine the finning needed to achieve the required conductance and the overall canister length to accommodate the required PCM weight.

Canister Requirements:

- PCM Weight -

$$W = \frac{Q\tau}{H_f} = \frac{80(3.412)}{85.5} = 3.19 \text{ lb} \xrightarrow{\text{use}} 3.5 \text{ lb}$$

$$W = 3.5 \text{ lb}$$

- Volume -

$$V = \frac{W}{\rho_{liq}} = \frac{3.5}{53.6} = .0653 \text{ ft}^3 = 113 \text{ in.}^3$$

- Length -

From Fig. B-2, at f = 10 fins/in. and t = .016 in.

$$\frac{W}{L} = .17 \text{ lb/in.}$$

thus,

$$L = W/.17$$

$$L = 20.6 \text{ in.}$$

- Conductance -

$$K = \frac{Q}{T_{HP} - T_{melt}}, \qquad Q = 40 \text{ watts} \qquad T_{HP} - T_{melt} = 139 - 135.5 = 3.5°F$$

$$K = \frac{40\ (3.412)}{3.5}$$

$$K_{req'd} = 39\ \frac{BTU}{hr\ °F}$$

On a per unit length basis,

$$\frac{K}{L}_{req'd} = \frac{39}{20.6} = 1.9\ \frac{BTU}{hr\ in.\ °F}$$

As seen from Fig. B-1, at f = 10 fins/in. and t = .016 in., the available effective conductance is 9 BTU/hr in. °F or over four times what's needed. The overall conductance of the canister is 185 BTU/hr °F.

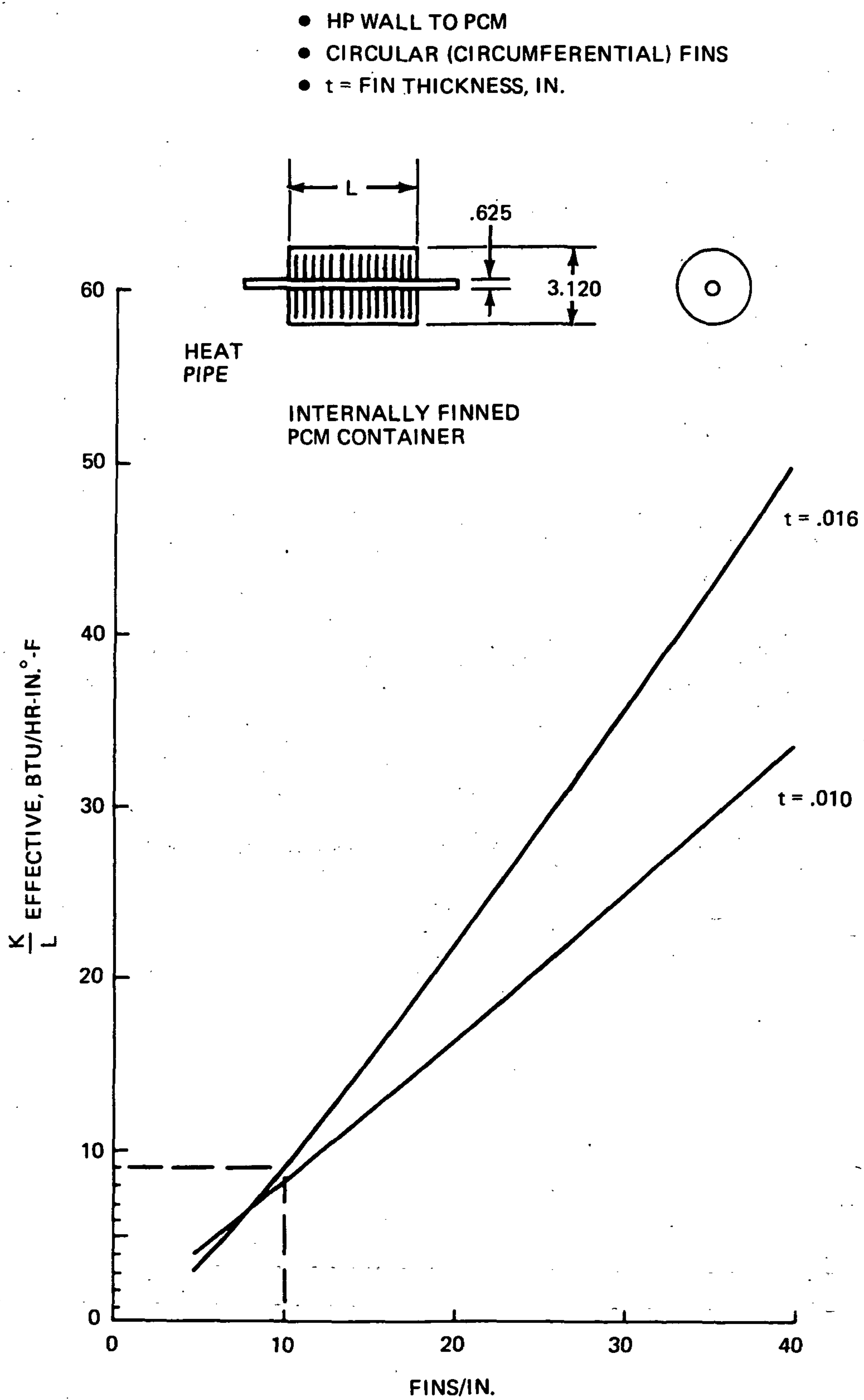

Fig. B-1 Effective Conductance

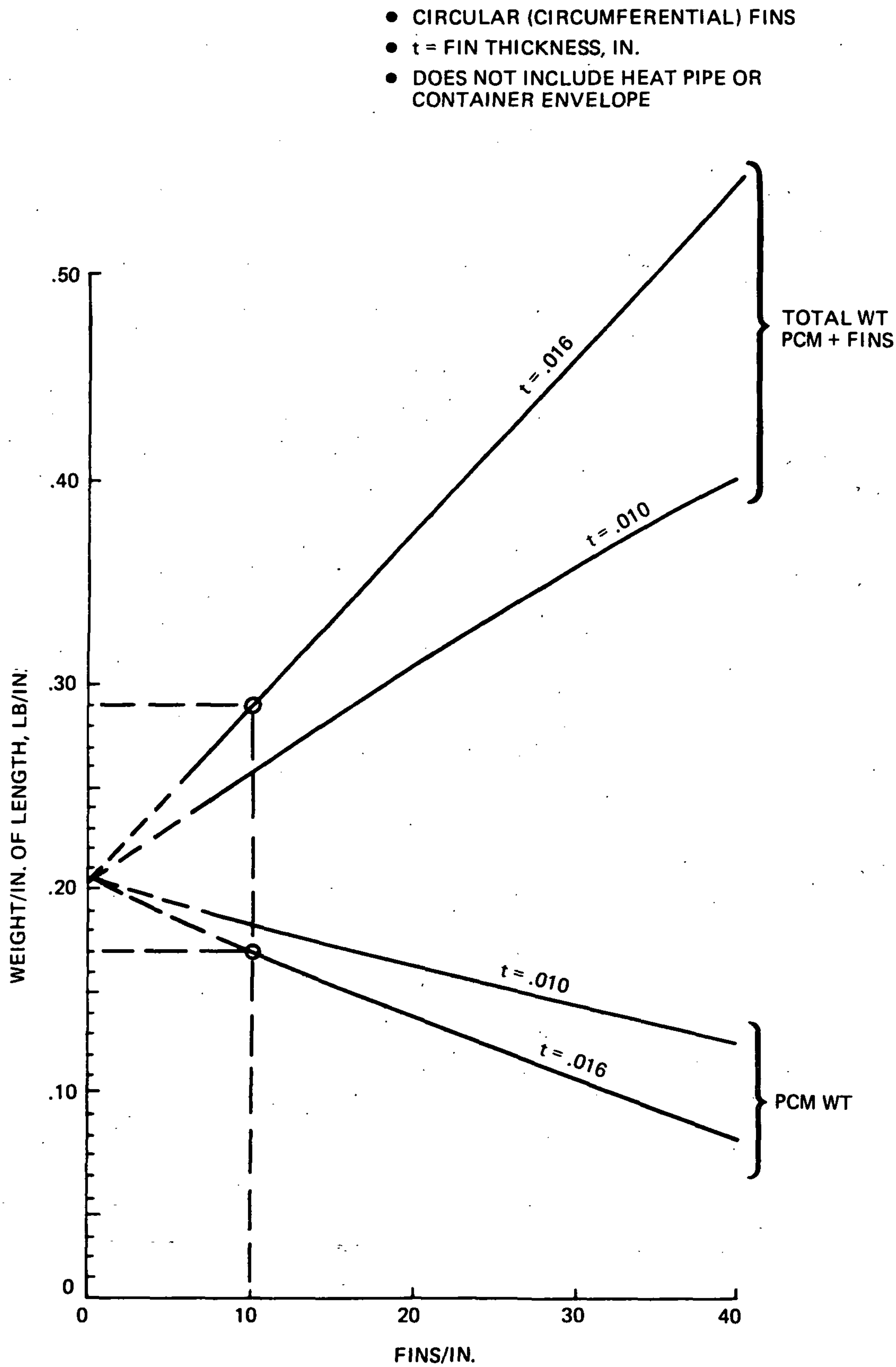

Fig. B-2 PCM Weight

Appendix C

DIODE HP THERMAL BENCH TEST DATA

Data Sheet	Test/Mode	Tilt, in.	Sink Temp., °F	Page
C.1	Previbration/Normal & Reverse	0, .325	-10, 57	C-2
C.2	Previbration/Normal & Reverse	.65, .975	57	C-3
C.3	Previbration/Normal	0, .325	95-120	C-4
C.4	Previbration/Normal	.65 .65 (Favorable)	85 58	C-5
C.5	Postvibration/Normal & Reverse	0	-10, 60	C-6
C.6	Postvibration/Normal	0, .50	115, 60	C-7

PREVIBRATION DIODE HP BENCH TEST DATA

C.1	T/C	Normal Mode												Reverse Mode
Heater Power (#1)														
Volts		13.03	16.030	13.92	17.92	22.54	25.		13.92	17.92	20.0	22.54		-
Amps		1.03	1.275	1.11	1.43	1.80	1.99		1.109	1.42	1.59	1.796		-
Watts		13.42	20.43	15.45	25.62	40.57	50.		15.4	25.5	31.9	40.5		-
Tilt (in.)		0	0	0	0	0	0		.325	.325	.325	.325		0
Location	T/C													
Sink Temp														
Inlet	39	- 34.5	-16.0	54.0	53.5	54.0	54.		54	54	54.5	54.5		119
Outlet	40	- 6.0	+52.0	53.5	53.0	54.0	54.		54	54	54.5	54.5		119
Flange	37	- 9.5	+58.0	55.5	55.5	56.0	57		55	56	56	56		117
	38	- 9.5	+62.0	55.0	56.0	57.0	57.5		56	56.5	58	57		117
Evaporator														
Flange	25	- 6.0	+70.5	58.5	63.0	71.0	90		60	62	66	84		74
	26	- 9.5	+69.0	57.5	61.0	69.0	88		59.5	61	65	82		76
Wall	27	- 2.0	+70.0	59.0	63.0	70.0	88		59.5	61	65	82		74
	28	- 9.5	+69.0	57.0	60.5	68.0	87		58	59.5	64	81		76
Adiabatic	29	- 9.5	+69.0	57.0	60.5	68.0	87		58	59.5	64	81		81
	30	- 9.0	+69.0	57.0	60.5	67.5	84.5		58	59.5	64	80		117
Condenser														
Wall	31	- 8.0	+68.0	57.0	60.0	66.0	62		58	59.5	63	60		117.5
	33	- 10.0	+61.0	56.5	58.5	57.5	60		57.5	57.	57	57		118
Flange	32	- 11.0	+64.0	55.0	55.5	57.0	58		55	56	58	58		118
	34	- 13.0	+59.0	55.0	55.0	55.5	56.5		55	55	56	56		118
Reservoir	35	- 15.5	+52.0	55.0	54.5	55.0	56		54.5	55	55	56		118
	36	- 14.0	+50.0	55.5	55.0	55.0	56		55.5	55.5	56	56.5		116

PREVIBRATION DIODE HP BENCH TEST DATA

C.2	T/C	←				Normal Mode				→	Reverse Mode		
Heater Power (#1)													
Volts		13.92	17.92	20.	22.54		13.92	17.92	20.	22.54		-		
Amps		1.11	1.428	1.59	1.796		1.11	1.428	1.59	1.796		-		
Watts		15.4	25.5	31.9	40.5		15.4	25.5	31.9	40.5		-		
Tilt (in.)		.65	.65	.65	.65		.975	.975	.975	.975		.975		
Location	T/C													
Sink Temp														
Inlet	39	54	54.5	54.5	54.5		54	54.5	54.5	54.5		117		
Outlet	40	54	54.5	54.5	54.5		54	54.5	54.5	54.5		117		
Flange	37	56	56.5	57	56.5		55.5	56	56	57		110		
	38	56	57.5	57.5	57.		55.5	56	57	57.5		111		
Evaporator														
Flange	25	60	63	64	86		68	75	80	88		62		
	26	60	62	62.5	84		68	74	78.5	87		61		
Wall	27	60	62	63	84		68	74	78.5	87		62		
	28	58	61	61	83.5		67	73	78	85		61		
Adiabatic	29	58	61	61	83.5		67	73	77.5	85.5		63		
	30	58	61	61	81.		66	72	76	83.		111		
Condenser														
Wall	31	58	60	61	60.5		57	58	60	60.5		110.5		
	33	57	58	61	58.5		56	56	57	59.		112		
Flange	32	56	57	57	57		56	57	58	58.		114		
	34	55	56	61	56		55	56	56	57		113		
Reservoir	35	55	55.5	56	56		55	56	56	56		112		
	36	56	56	57	57		56	56	57	57		108		

PREVIBRATION DIODE HP BENCH TEST DATA

C.3		Normal Mode												
Heater Power (#1)														
Volts		13.92	17.92	20	22.54	25	27.49		13.92	17.92	20.	22.54		
Amps		1.11	1.43	1.59	1.796	1.99	2.19		1.11	1.428	1.59	1.8		
Watts		15.5	25.5	31.9	40.5	50	60.2		15.5	25.5	32.	40.5		
Tilt (in.)		0	0	0	0	0	0		.325	.325	.325	.325		
Location	**T/C**													
Inlet	39	119.5	119	108	105	100	97		89	86	84	83		
Outlet	40	120.5	120	108	105	100	97		89	86	84	83		
Flange	37	119.5	120	109	106	101	98		90	88	85	84		
	38	120	120.2	110	108	101.5	100		90.5	89	86	85.5		
Evaporator														
Flange	25	122	125	116	118	133	141		95	94	106	112		
	26	121	124.5	115	117	131	140		94.5	93.5	104.5	110		
Wall	27	121	123	114.5	116	130	138		94	93	104.5	110		
	28	122	124	115	116	131	139		94	93	104.5	110		
Adiabatic	29	122	124	115	116	131	139		94	92.5	104.5	110		
	30	122	124	115	116	129.5	135		94	92.5	103.5	108		
Condenser														
Wall	31	121.5	123	113	114	107	104		93	92	88	88.5		
	33	122	123.5	112	112	105	100		91	90	87	87		
	32	120.5	121.0	110	108	104	102		91	89	86	86		
Flange	34	120.5	120.5	110	106	102	109.5		90	88	85.5	85		
Reservoir	35	120	120	108	105	102	109		90	87	85	84		
	36	117	117	107	104	100	107		89.5	86	84	84		

POSTVIBRATION DIODE HP BENCH TEST DATA

C.4		Normal Mode									
Heater Power (#1)											
Volts		13.92	17.92	20.00	22.54		13.92	17.92	22.54	25.	27.49
Amps		1.11	1.428	1.59	1.8		1.11	1.428	1.796	1.99	2.19
Watts		15.5	25.5	32	40.5		15.5	25.5	40.5	50	60.2
Tilt (in.)		.65	.65	.65	.65		-.65	-.65	-.65	-.65	-.65
Location	T/C										
Sink Temp											
Inlet	39	85	84.5	83	83		54	54.5	54	54.5	55
Outlet	40	85	84.5	83	83		54	54.5	54	54.5	55
Flange	37	85	85	84	85		56	57	58	57.5	58
	38	85	85.5	84.5	86		56	57	58	58	59
Evaporator											
Flange	25	96.5	105.5	112	126		59.5	61.5	65	83	94
	26	96	104	111	124		58.5	60	63.5	81	92
Wall	27	95.5	104	110	123.5		59	60.5	63.5	81	92
	28	96	104	111	124		57.5	59	61.5	79	90
Adiabatic	29	96	104	111	124		57.5	59	61.5	79	90
	30	95	102	107	115		57.5	59	61.5	78	88
Condenser											
Wall	31	86	87	87	99		57.5	59	61.5	62.5	64
	33	86	87	85	99		57	58	61	60	62
Flange	32	85.5	86	87	96		56	56	57	58	59
	34	85	85.5	84.5	96		56	57	58	57	58
Reservoir	35	85	85	84	95		56	57	58	56.5	58
	36	84	84	83	94		57.5	58	60	57	58

POSTVIBRATION DIODE HP BENCH TEST DATA

Post-Vibration C.5	T/C	Normal Mode											Reverse Mode	
Heater Power (#1)														
Volts		7.2	10	12.5	14	16.8		10	12.5	16.6			-	
Amps		1.25	1.55	2.1	2.35	2.85		1.5	2.	2.75			-	
Watts		7	15.15	26.25	32.90	48.02		15	25	45.6			-	
Tilt (in.)		0	0	0	0	0		0	0	0			0	
Location	T/C													
Sink Temp														
Inlet	39	-31	-34	-38	-38	-50		57	57	55			123	
outlet	40	-37.5	-48	-49.5	-49.5	-39.5		58	58	56			121	
Flange	37	+3	-4	-7.5	-5	-5		60	60	61.5			119	
	38	-9	-18	-23.5	-21	-19.5		60	60	61.5			118	
Evaporator														
Flange	25	-14	-16	-11	-4	+16		62	64	69			93	
	26	-10.5	-14	-9	-2	+12		62	64	69.5			94	
Wall	27	-15	-17	-13	-6	+11		60.5	62	66			93	
	28	-10	-11	-7	-5	±12		60.7	62.5	66			94	
Adiabatic	29	+2	+1	-6	+14	+30		71.5	75	84			95	
	30	-9.5	-11.5	-9	-3	+8		61.8	63	66			119	
Condenser														
Wall	31	-14	-23	-26	-23	-19		60.5	62	66			122	
	33	-12	-21	-24	-22	-19		59.0	62	66			122	
Flange	32	-17.5	-25.5	-29.5	-27	-23.5		59.0	59.5	61			122	
	34	+2	-4	-9	-9	-9.5		58.5	58	59			122	
Reservoir	35	-9	-20	-22	-21	-20		60.0	60	61			119	
	36	-19	-29	-34	-32	-31.5		58	58	58			122	

POSTVIBRATION DIODE HP BENCH TEST DATA

Post-Vibration C.6								Normal Mode						
Heater Power (#1)														
Volts		10	12.5	16.	17.5	19.		10	12.5	15.5	9.6	12.5	14.5	15.5
Amps		1.6	2.05	2.65	2.9	3.2		1.6	2.05	2.6	1.6	2.1	2.4	2.6
Watts		16	25	42	51	60		16.	26	40	15	26	35	40.
Tilt (in.)		0	0	0	0	0		.50	.50	.50	.50	.50	.50	.50
Location	T/C													
Sink Temp														
Inlet	39	123	115.5	112	109	109.5		112	103	100	57	57	57	57
Outlet	40	121	114	110	108	106.		110	102	99	58	58	58	58
Flange	37	120	115	112	110	109		110	103	100	60	60.5	60.5	60
	38	120	115	112	110.	109		111	104	102	60	61.	61.5	62.5
Evaporator														
Flange	25	123	121	121	120	120		116.5	113	113	62	64	66	70
	26	123	121	121	120	120		116	113	113	62	64	66	71
Wall	27	123	119	118.5	116	116		116	111	111	60.5	62	64	68
	28	123	119	118.5	116	116		116	111	111	60.5	62	64	68
Adiabatic	29	120.5	122	127	128	129		116	116	119	68	72	78	83
	30	121	118	116.5	114.5	114		114	110	109	61.5	63	64	68
Condenser														
Wall	31	123.	118.5	117.5	115.5	115.5		115	110	108.5	60.5	62	64	67.5
	33	123.	118.5	117.5	115.5	115.5		113	105	102	60.5	62	64	63
Flange	32	122.5	117	115	112	112		113	106	104	59	60	60	62
	34	122	117	113.5	111.	110		111	104	100	58.5	58.5	59	58
Reservoir	35	121	116	113.5	111.5	111.		110	113	100	60	60.5	60.5	59
	36	122	116	113.5	111.	110		111	113	100	58	58.5	58	58

Appendix D

TRANSPORT HP THERMAL BENCH TEST DATA

Data Sheet	Test	Tilt, in.	Sink Temp, °F	Page
D.1	Normal Mode (1st Series)	.146	55, 90	D-2
D.2	Normal Mode (1st Series)	.587	55, 95	D-3
D.3	Normal Mode (1st Series)	.880	56, 105	D-4
D.4	Normal Mode (2nd Series)	.146, .587, .88	55	D-5
			Q, watts	
D.5	PCM Melt	.587	40	D-6
D.6	PCM Melt	.587	80	D-8

TRANSPORT HP BENCH TEST, NORMAL MODE (1ST SERIES)

D.1

Tilt = .146[*]

Normal Mode	Q T/C	5W	15W	40W	60W	150W	5W	15W	40W	60W	100W	150W		
Condenser Spray Bath Temp (°F)		56	55	55	55	55	96	89	86	88	89	88		
Htr Plate	1	59	59.8	62.5	65.	75	100	93	93.5	97	104.5	108		
	2	59	59.8	63.	65.5	76.5	100	93	93.8	97.5	104.5	108		
Evaporator Wall	3	59	59	60.5	62.5	67.	98.5	92	91.	94.	98.	99.8		
	4	59	59	61	62.5	67.	98.5	92	91.	94.	98.	99.5		
Flange	5	59	59.5	62	64.	72.	100	92.5	92.8	96.	102.5	105.5		
	6	59	59.5	62.5	64.5	73.5	100	92.5	93.0	96.	102.5	105.		
Adiabatic	7	59	59.	60.	61.5	67.	98.5	91.5	90.5	93.	97.5	99.5		
PCM	8	59	59	60	61.5	67.	98.5	92.	90.5	93.	97.	99.		
	9						98.5			93.	97.	98.5		
	10						98.5			93.	97.	98.5		
	11									93.	97.			
	12									93.	97.			
	13									93.	97.			
	14						98.5			93.	97.			
	15						99			93.	97.			
	16						99	92	90.5	93.	97.			
	17	-	-	-	-	-	-	-	-	-	-			
	18						99	92	90.5	93.	97.			
	19	59	59	60	61.5	67.	99	91.5	90.5	93	97.	98.5		
Adiabatic	20	58.5	58.5	59.8	61.	67.	98.5	91.	90.5	93	97.	99.		
Condenser Wall	22	57.5	57.5	59.	60.	62.5	98.	90.	90.	92	94.5	95		
	21	57.5	57.5	58.	59.5	63.	98	90.	90.	92	94.5	95.5		
Flange	24	57.	57.	58.5	59.5	61.	97	89	90	92	94.	94.		
	23	57.	57.	57.5	59.0	62.	98.	89.5	89.8	91.5	94.	94.8		
Heater Power (#1) Watts		5.3	15.3	42.9	61.6	148.5	5.2	15.3	42.9	62.4	106.	149.8		

TRANSPORT HP BENCH TEST, NORMAL MODE (1ST SERIES)

D.2 Tilt = .586"

Normal Mode	Q / T/C	15W	40W	60W	80W		15W	40W	60W					
Condenser Spray Bath Temp		56	56	56	56		95.	95.	96.					
Htr Plate	1	61	66.5	68.	69.5		102.	106	106.5					
	2	61	68.0	70	71.		103.	106.5	108					
Evaporator Wall	3	60.5	64	65.	66.		101.	103	103					
	4	60.5	64	65.	66.		101.	103	103					
Flange	5	61.	65.5	67.	68.		102.	105	105					
	6	61.	67.	68.5	69.5		102.5	106	106.5					
Adiabatic	7	60.5	64	65.	66.		101.	103	103					
PCM	8	60.8	64	65	66		101	103	103					
	9	60.8												
	10	60.8												
	11	60.8												
	12	60.8												
	13	61												
	14	61.												
	15	61.												
	16	61.												
	17	-												
	18	60.8												
	19	60.8	64	65	66		101	103	103					
Adiabatic	20	60.5	64	65	66		101	103	103					
Condenser														
Wall	22	57.5	59	59.5	59.5		99	98.5	98.5					
	21	58	61.5	62.5	61.5		99.5	100.5	100.5					
Flange	24	57.5	59	59.5	59.5		99.	99.5	99.5					
	23	58.5	61.	62.	62.		99.5	100.5	100.5					
Heater Power (#1) Watts		15.6	42.9	61.2	80.8		15.6	43.2	60.5					

TRANSPORT HP BENCH TEST, NORMAL MODE (1ST SERIES)

D.3

Tilt = .88"

Normal Mode	Q T/C	15W	40W	60W		15W	40W	60W						
Condenser Spary Bath Temp		56	56	56		106	104.	102.						
Htr Plate	1	63.5	68	70.5		112.5	113.	112.5						
	2	65	69.5	72		114	115	115.						
Evaporator Wall	3	63	66	67.5		111.	110.5	110.						
	4	63	66	67.5		111.	110.5	110.						
Flange	5	63.5	67	69.		112.5	112	111.5						
	6	64.5	68.5	70.5		113.	114.	113.						
Adiabatic	7	62.5	65.5	67.5		111.4	110.5	110.						
PCM	8	62.5	65.5	67.5		111.4	110.5	109.5						
	9					111.4	110.5							
	10					111.	110							
	11													
	12													
	13													
	14													
	15													
	16													
	17													
	18													
	19	62.5	65.5	67.5		111.	110	109.5						
Adiabatic	20	62.5	65.5	67.5		111.4	110.5	110.						
Condenser Wall	22	57.5	57	58		108.5	106.	105.						
	21	59.	61	62.5		109.	108	105.						
Flange	24	57.5	57	58		108.5	106	105.						
	23	59	61	62.5		109.	108.5	107.						
Heater Power (#1)														
Volts		8.5	14.3	17.4		8.5	14.3	16.5						
Amps		1.82	3.1	3.6		1.82	3.1	3.42						
Watts		15.3	44.3	62.6		15.3	44.3	56.4						

TRANSPORT HP BENCH TEST, NORMAL MODE (2ND SERIES)

D.4

Normal Mode (2nd Series)	T/C	Tilt = .146" 40W	80W	150W	430W	Tilt = .587" 40W	80W	320W	.88" 60W
Cold Plate Temp		55	55	55	55	55	55	55	55
Htr Plate	1	66	71	82.5	124	65	69.5	109	73
	2	66	71.5	82.5	124	66	70.5	109	75
Evaporator Wall	3	63.8	67	75	106	63.5	66	94.5	70
	4	64.5	67	75.5	105.5	64	66	94.2	70
Flange	5	65.2	69	79	115	645	68	102	71.2
	6	65.8	69.8	79.5	114	65	68.3	101	72
Adiabatic	7	63.8	69	75	106.5	63	65.5	95	70
PCM	8	63.8	67	75	106	63.5	65.5	95	70
	9				105.5				
	10								
	11								
	12								
	13								
	14								
	15								
	16								70
	17								-
	18								70
	19	63.8	67	75	105.5	63.5	65.5	95	70
Adiabatic Wall	20	63.5	67.	74.5	105.5	63	65.5	94.2	70
	22	63.9	67	74.2	103	62.8	65	93	68
	21	63.8	67	74.5	104.5	63	65	93.5	62.5
Flange	24	62.2	65	71.8	93	61	63.5	85	68
	23	62.2	65	72	95	61.8	63.5	86	63
Heater Power									
Volts		14.5	20.	27.5	46.4	14.5	19.5	40.	17.3
Amps		3.0	4.1	5.5	9.27	3.0	4.	8.	3.56
Watts		43.5	82.	151.	430.	43.5	78.	320.	62.

TRANSPORT HP BENCH TEST, PCM MELT

D.5

Q = 40 Watts
Tilt = .587 in.

PCM Mode	T/C	Time (Minutes) 0	5	10	20	40	60	90	120	150	180	210	240	280
Htr Plate	1	80	87.5	91	96	106	114.2	123.8	128	130.2	132	133.5	134	134
	2	80	88	92	98	108	116.5	125.8	130.5	132.6	134.2	135.5	136	136.2
Evaporator														
Wall	3	80	85	88	94	103	112	121	125	128	129.5	130.2	130.8	131
	4		85	88	94	103	112	120.5	125	127.5	129	130.	130.5	131
Flange	5		87	90	95	105	113.8	122.2	127	129.5	131	132.2	133.	133
	6	80	87	90.5	97	106.5	115.8	123.7	129	131	132.5	134.2	134.2	134.5
Adiabatic	7	80	85.4	88	94	103.5	112	121	126	128	130	131	131.5	132
PCM	8	80	84.8	88	94	103	112	121	125.8	127.8	129	130.2	130.5	131
	9		84.4	87.8	93	102.5	111.5	120	125	127.	128.5	130.	130.2	130.8
	10		84.2	87	93	102.2	111	120	125	127	128	129.5	129.8	130
	11		84.	87.8	93	102.2	111.5	120		127	129	130	130.2	130.5
	12		85.	88.	93.8	103	111.5	120.5		127.5	129	130.	130.2	131
	13		84.2	87.5	93	102.2	111.	120		126.5	128.5	129.8	130	130.4
	14		84.2	87.5	93	102	111	120		126.8	128.	129.5	130.	130.2
	15		84.4	87.8	93	102.2	111.	120		127	128.2	129.5	130.	130.2
	16		85	88	93.5	103	111.5	120.2	125	127	128.4	129.8	130.2	130.8
	17		-	-	-	-	-	-	-	-	-	-	-	-
	18		84.4	88	93	102.4	111.	120	124.8	126.5	128	129.2	130.	130
	19	80	85	88	93.5	103	111.5	120.5	125	127	128.8	129.8	130.2	130.5
Adiabatic	20	80	85.5	89	94	103.8	112.	121	126	128	129.5	130.8	131.5	131.8
Condenser (ins)														
Wall	22	80	85	88	94	103	111	120	125	127	129	129.8	130.2	131
	21		84	87.5	93	102	111	120	125	127	129	129.8	130.2	131
Flange	24		84	87.5	92.5	102	110.2	119	124	126	128	129.	129.8	130
	23	80	84	87.5	93	102.2	111.	120	125	127.5	129	130	130.2	131
Htr Power (#1)														
Volts		14.1	14.2	14.2	14.1	14.	14.4	14.1	14.1	14.1	14.2	14.15	14.8	14.1
Amps	-	2.9	2.95	2.95	2.9	2.9	3.35	2.9	2.9	2.9	2.95	2.95	3.05	2.9
Watts		40.9	41.9	41.9	40.9	40.9	40.9	40.9	40.9	40.9	41.9	41.9	43.9	40.9

TRANSPORT HP BENCH TEST, PCM MELT

D.5 Continued

Q = 40 Watts
Tilt = .587 in.

PCM Mode	T/C	Time (min) 300	320	330	340	350	360	370	Cool Down 5	10	15	20	25	30
Htr Plate	1	135	136.5	138.5	140.5	142.2	145	148	126	122	119	113	102	88
	2	137.5	13 9.	140.8	142.8	144.8	148	150	127	122	119	113	102	88
Evaporator Wall	3	132	134	135.5	137.2	139.2	142	145						
	4	132	133.5	135.2	137	139	143	144.5						
Flange	5	134	135.5	137.2	139.2	141.2	144	147						
	6	136	137	139.2	141.2	143	146	148.2						
Adiabatic	7	132.4	134.5	136	138	140	143	146						
PCM	8	132	134	139.9	137.5	139.9	142.2	145.	128	124	120	114	102	88
	9	131.8	133	139	137	139	142	144.4	128	126	123	117	105	90
	10	130.2	133	139	137	139		144.2	130	129	128	127	117	92
	11	131.8	133	139.5	137	139.2		144.4	129	128	126	120	107	90
	12	131.8	133	139.7	137.2	139.2		145.	128	126	121	114	102	88
	13	131.5	133	138.3	136.8	138.8		144.2	128	127	123	116	104	90
	14	130.2	133	139	136.8	138.8	141.8	144.2	128.5	128	126	122	108	90
	15	131	133	138.8	136.8	138.6	142.	144.2	128.	127	123	116	104	89
	16	131.5	133	139	137	139	142	144.4	128.	125	120	113	101	87
	17	-	-	-	-	-	-	-	-	-	-	-	-	-
	18	130	133	134.5	136.8	136.8	141	144	129	128	126	124	103	88
	19	130.8	133.5	135	137.2	139	142	145	128	125	120	122	100	86
Adiabatic	20	131.2	134.2	136	138	140	143	146						
Condenser Wall	22	131.2	133	134.8	137	139	14.5	144.2						
	21	131.2	133	134.8	137	139	141.5	144.2						
Flange	24	130.4	132.5	134.2	136	138	140.5	143.8						
	23	131.8	133.5	135.2	137	139.5	142	145						
Htr Power (#1) Volts		14.1	14.1	14.1	14.1	14.1	14.1	14.1						
Amps		219	2.90	2.90	2.90	2.90	2.9	2.9						
Watts		40.9	40.9	40.9	40.9	40.9	40.9	40.9						

TRANSPORT HEAT PIPE THERMAL BENCH TEST

D.6

Q = 80 Watts
Tilt = .587 in.

PCM Mode	T/C	Time (Minutes)									Cool Down			
		0	5	10	20	40	60	90	120	150	5	10	15	20
Htr Plate	1	77.5	91	98	109	126	134	138	139.8	154	122	119	114	101
	2	77.5	94	100.4	110.5	125.8	133	136.5	138	153	122	119	114	101
Evaporator Wall	3	77.5	87	93	103.5	119.7	127	131	132.8	147	122	119	114	101
	4		87	92.8	103.2	119	126.5	130	132.2	146.5	122	119	114	101
Flange	5		90	96.5	107.5	124	132.5	136	137.8	151.2				
	6	77.5	92	98.5	109	123	130.5	134	136.2	150.4	122	119	114	101
Adiabatic	7	77.5	88	94	104.4	120	128	131.5	133	148.2	122	119	114	100
PCM	8	77.5	87.5	93.5	104	119.8	127	130.5	132.5	147.8	124	120	116	101
	9	77.5	86.5	92.5	103	118.2	126	129.8	131.5	147	126	123	118	104
	10		86.	92.	102.4	118.	125	129	130	146	128	128	127	116
	11		86.2	92.2	103	118	126	129	131	146	128	126	122	105
	12		87.	93	103.2	119	126	130	132	147	126	122	116	101
	13		86.2	92	102.5	118	125.8	129	131	146	127	124	118	103
	14		86.2	92	102.5	118	125	129	130	146	128	127	124	108
	15		86.5	92	102.6	118	125	129.5	130.2	146	127	124	118	103
	16		87.	93	103.4	119	126	129.5	131.5	146	126	122	116	100
	17		-	-	-	-	-	-	-	-	-	-	-	-
	18		86.5	92.4	103	120	125	128.5	130	146	128	127	124	103
	19	77.5	87.5	93.8	103.5	119	126	129.5	131.8	147	126	121	115	99
Adiabatic	20	77.5	88.5	94.6	104.8	120	127.5	131	133	148	120	117	112	97
Condenser (ins)														
Wall	22	77.5	88	94	103.8	119	126.2	130	132	147	105	103	99	87
	21	77.5	88	94	104	119.8	127	130	132.2	147	96	94	88	78
Flange	24	77.5	86.2	92	102	117.8	125	129	131.	145	106	103	100	88
	23	77.5	88	93.5	103.8	119.	126.2	130	132	147	94	92	88	78
Htr Power (#1)														
Volts		19.8	19.8	19.8	19.8	19.6	20.	19.8	19.8	19.8				
Amps		4.2	4.2	4.2	4.2	4.1	4.3	4.2	4.2	4.2				
Watts		83.2	83.2	83.2	83.2	80.6	86.	83.2	83.2	83.2				

Appendix E

MODULAR HEAT SINK SYSTEM TEST DATA

HP/PCM MODULAR HEAT SINK SYSTEM TEST, STEADY STATE, NORMAL MODE (Sheet 1 of 2)

E.1

Test #'s		1	2	3	4	5	6	7	8	9	10	11	12	
Normal Mode	Q T/C	5W	15W	40W	5W	15W	40W	5W	15W	40W	5W	15W	40W	
Sink Temp (°F)		-40	-40	-40	30	30	30	70	70	70	110	110	110	
Htr Plate	1	-1.5	+4	+25	-	51.5	65.5	71.5	76.0	83.0	114.5	119	125.	
	2	1.5		25	38	51.5	65.5	71.5	76.0	83.0	114.5	119	125.	
Evaporator														
Wall	3	-1.0		24	38.5	51.3	64.0	71.5	75.0	81.0	114.	117	122.	
	4	-1.0		24	38.5	51.3	64.0	71.5	75.1	81.5	114.	117	122.5	
Flange	5	-2		25	38	51.0	65.0	71.5	76.0	82.5	114.5	118.5	124.	
	6	-1.5		24.5	38	51.3	65.0	71.5	75.3	82.5	114.5	118.5	124.	
Adiabatic	7	-1.5		23	38	50.3	63.5	71.5	75.0	81.0	114.	118	122.5	
PCM	8	-1.5		23	38	50.5	63.5	71.3	75.0	81.0	114	118	122.5	
	9	-1.5		23.5	38	51.0	63.5	71.2	75.0	81.0	114		122.	
	10	-1.5		23.0	37.7	51.0	63.5	71.0	75.0	81.0			122.	
	11	-1.5		23.0	37.7	51.0	63.5	71.0	75.0	81.0			122.	
	12	-1.5		23.0	38	51.0	63.5	71.0	75.0	81.0			122.	
	13	-1.0		23.0	38.5	51.0	63.5	71.0	75.0	81.0			122.	
	14	-1.0		23.0	38	51.0	63.5	71.0	75.0	81.0			122.	
	15	-1.0			38	51.0	63.5	71.0	75.0	81.0			122.	
	16	-1.0	+4	23.0	38	51.0	63.5	71.0	75.0	81.0			122.	
	17	-30	+19	37.0	50	66.5	64.5	70.5	71.0	81.0			98.	
	18	-1.0	+4	24.5	38.3	51.0	63.5	71.2	75.0	81.0			122.	
	19	-1.0	+4	24.5	38	51.0	63.5	71.1	75.0	81.0	114.	118	122.	
Adiabatic	20	-2.0	+3.5	23.0	38	50.3	63.5	70.0	75.0	81.0	114.	117.5	112.5	
Condenser														
Wall	21	-20	-11	15	30.5	42.0	57.7	68.0	70.2	76.2	111.	114	122.	
	22	-4	+2	21.5	31	47.3	60.3	68.0	71.2	78.5	111.	115	120	
Flange	23	-5	+2	22.0	31.5	46.5	59.0	68.5	71.2	76.4	111.5	114	119.5	
	24	-27	-21	3	31.5	42.5	55.5	68.2	70.3	75.1	110	113	118.	

HP/PCM MODULAR HEAT SINK SYSTEM TEST, STEADY STATE, NORMAL MODE (Sheet 2 of 2)

E.1

Test #'s		1	2	3	4	5	6	7	8	9	10	11	12
Normal Mode	Q / T/C	5W	15W	40W	5W	15W	40W	5W	15W	40W	5W	15W	40W
Sink Temp (°F)		-40	-40	-40	30	30	30	70	70	70	110	110	110
Diode Evap.													
Flange	25	-4	+1	23.5	33.5	45.5	58.7	70.0	72.0	77.5	111	114.5	120
	26	-25	-19	4	34	43.5	57.3	70.0	72.0	77.6	110.5	114.5	120
Wall	27	-4	+2	22.0	34	43.5	56.5	70.5	71.9	77.7	110.	114.	119
	28	-24	-18	1.5	33.3	43.5	56.5	70.7	72.0	77.0	110.	114.	119
Adiabatic	29	-26	-23	2	33	43.5	55.5	70.5	72.0	76.0	111.	115.	120
	30	-26	-23	1	33.5	42.5	55.5	69.8	72.0	76.0	113	115.	120
Diode Cond.													
Wall	31	-33	-30	-13.5	33.3	42.5	51.5	69.8	71.5	77.0	112	114	116.
	33	-39	-39	-27.5	32.5	31.0	35.5	70.2	71.5	76.0	113	113	113
Flange	32	-41	-37.5	-25.0	33	37.0	42.7	70.0	70.5	73.2	114	113	114
	34	-43	-41	-31.0	33	28.7	34.0	69.0	71.5	73.5	113	113	115
Reservoir	35	-44	-42.5	-31.0	31	4.0	7.7	69.0	71.5	75.2	114	111.5	112
	36	-45.5	-45.	-34	22	-16.0	-14.5	68.3	71.0	71.0	113	108.5	109
Sink Temp													
Inlet	39	-42	-52	-47	-35	-45.0	-46.5	68.3	70.0	69.0	86.	88	93
Outlet	40	-44	-56	-10	34.5	38.5	44.5	70.2	71.2	73.0	112	104	97
Flange	37	-53	-40	-37	32	35.7	42.5	69.0	70.5	72.0	113	110	109
	38	-55	-43	-32.5	30.5	29.5	33.3	69.3	70.6	72.3	113	112	110.5
Heater Power (#1)													
Volts		5.3	9.2	15.1	5.3	9.1	15.3	5.3	9.2	15.4	5.6	9.3	15.3
Amps		.94	1.54	2.58	.94	1.6	2.73	.95	1.65	2.75	1.0	1.62	2.73
Watts		4.98	14.17	39.	4.98	14.56	41.77	5.3	15.2	42.35	5.6	15.0	42.

HP/PCM MODULAR HEAT SINK SYSTEM TEST, STEADY STATE, REFLUX MODE (Sheet 1 of 2)

E.2

Reflux Boiler Mode	Q / T/C	5W	15W	40W	60W	100W	130W
Sink Temp (°F)		110	110	110	110	110.	110.
Htr Plate	1	114.	117	122.	123	129	133
	2	114.	118	122.5	123	129.5	126
Evaporator Wall	3	112.5	116	118	120.5	123.5	126
	4	113.	117	120	121.	124.	127
Flange	5	113.5	117	121.5	124	128.	131
	6	114.	118	122.	124	128.	131
Adiabatic	7	112.	115	118	120.	123	125.5
PCM	8	112	115	118	119.5	122.5	125
	9			117.5	119	122	125
	10						124
	11						124
	12						125
	13						124
	14						124
	15						124
	16						124
	17						-
	18					122	124
	19	112	115	117.5	119	121	124
Adiabatic	20	112	115	118	120	122.5	125
Condenser Wall	21	110	113	117.	119	122.5	125
	22	110	113	117.	118	121.	124
Flange	23	110	113	116.5	118	121	122
	24	108	112	113.	114	118	120

HP/PCM MODULAR HEAT SINK SYSTEM TEST, STEADY STATE, REFLUX MODE (Sheet 2 of 2)

E.2

Reflux Boiler Mode	Q T/C	5W		15W		40W		60W		100W		130W		
Sink Temp (°F)														
Diode Evap.														
Flange	25	112		115.5		117		118		121		122.5		
	26	111		115.5		116		117		120		122		
Wall	27	112		115.5		116		117		119.5		120.		
	28	112		115.5		116		116		119.5		119.		
Adiabatic	29	111		114		114		114.5		117.5		118.		
	30	110		112		114		114.		116		112		
Diode Cond														
Wall	31	110		111.		114.5		115.		117.5		118		
	33	110.		111.5		114.		114.		116		112		
Flange	32	110.		111.5		113.		112		114		117		
	34	110.		111.		113		113		115		113.5		
Reservoir	35	110.		111.		114		114		117		117		
	36	110.		111.		113		113		115		113.5		
Sink Temp														
Inlet	39	85		86.		86		87		88		88		
Outlet	40	108		109		108		104		105		104		
Flange	37	110		111.		113		111		113		111		
	38	110.5		111.		113		110		113		110		
Heater Power (#1)														
Volts		5.5		9.3		15.5		20.		23.		27		
Amps		1		1.7		2.76		3.6		4.		4.75		
Watts		5,5		15.8		42.78		72		92		128.		

HP/PCM MODULAR HEAT SINK SYSTEM TEST, TRANSIENT, 80-WATT LOAD (Sheet 1 of 2)

E.3

Level, Transient	T/C	Steady State	Time (Minutes) 0	5	10	20	40	50	60	80°F Cool down - Power Off 65	70	80	90	100
Sink Temp (°F)		110	207	207	207	207	207	207	207					
Q (Watts)		80	80	80	80	80	80	80	80					
Htr Plate	1	126		132	132	133	135	138	146	135	131.5	125	124.5	
	2	126		132	132	133	135	138	146	135	131.5	125	124.5	
Evaporator														
Wall	3	124		128	128	128	131	133	141	134	131.	124	124	
	4	124		128	128	128.5	131	134	141	134	131.	124	124	
Flange	5	126		130.5	131	131.5	134	137	145	134	131.5	125	124.5	
	6	126		130.5	131	131.5	134	137	145	134	131.5	125	124.5	
Adiabatic	7	124		128	128	129	131.5	134	142	134	131.	125	124.5	
PCM	8	124		127.5	128	128	131.5	134	142	135	131.	126	125	
	9			127.	127	127	130.	132.5	141	135	131.5	126	125	
	10			125.	127	127	130.	132.5	141	135	131.5	126	125	
	11			127.	127	128	130.	133	141	135	132.	126	126	
	12			126	126	126	129.5	132	141	135	132.	126	126	
	13			125	125	126	128.	131	140	135	132	126	126	
	14			125	125	125	127.	128	138.5	135	132.	126	126	
	15			125	125	125	127.	131	140.	134.5	131.5	126	126	
	16			125	125	126	129	133	141.	134.5	131.5	126	125.5	
	17			-	-	-	-	-	-	-	-	-	-	
	18			125	125	125.5	127.5	131	140.	135.	131.	125.5	126	
	19	124		125	125	126	128.5	133	141.	134.	131.	125.5	125.5	
Adiabatic	20	124		127.5	127.5	126.5	129	133.5	142	134.	130.5	125	124	
Condenser														
Wall	21	121		126	127	128	131	133.5	141.	130	127	122	121.5	
	22	121.5		126	125	126	129	131	140.	132	129	122.5	122.	
Flange	23	120.5		126	126	127	130	132	140	131	128	122	121.	
	24	118		124	125	126.5	129.5	131.5	138	127	124	119	118	

HP/PCM MODULAR HEAT SINK SYSTEM TEST, TRANSIENT, 80-WATT LOAD (Sheet 2 of 2)

E.3

Level, Transient	T/C	Steady State	0	5	10	20	40	50	60	65	70	80	90	100
			Time (Minutes)							80° Cool Down - Power Off				
Sink Temp (°F)		110	207						207					
Q (Watts)		80							80					
	T/C													
Diode Evap.														
Flange	25	120		128	128	129.5	132	134	142	131	128	120.5	120	120
	26	118		127	128	130.	132	136	142.5	130	126	119	120.	119
Wall	27	117.5		128	129	130.	132	135	143	130	126	120	119	118
	28	117.5		128	129	130.	132	135	142.5	129.5	126	120	119	118
Adiabatic	29	119		128	132.5	137.	138	141	146	130	127	120	120	119
	30	119		170	178	186	188	189	190	116	114	114	112	112
Diode Cond														
Wall	31	118		182	184	192.5	194	196	196	94	94	93	91	90
	33	116		183	184	193.	193.5	196.0	196	88	86	84	82	80
Flange	32	114		182	183	192.5	194	195.5	196	88	87	86	81.5	80.5
	34	111		184	185	193.	195	196.	197	83	82	81	78	75.5
Reservoir	35	110		181	184	193.	194	195.	195.	89	88	85	81.5	80
	36	106		183	184	193	194	196.	195.	82	81	80	77	75
Sink Temp														
Inlet	39	86		90	93	94	95	94	94	88	85	81	79	78
Outlet	40	106		124	130	138	138	148	138	82	82	80.5	78	76
Flange	37	110.5		183	184	192.	193	195	194.5	83	82	81	78	77
	38	110.5		184	185	193.	195	196	196	82	81	80	76	75
Heater Power														
Ckt #1 Volts		15.5		21.5	21.5	22.0	22	22	22	-	-	-	-	-
Amps		2.75		3.8	3.8	3.8	3.8	3.8	3.8	-	-	-	-	-
Watts		42.6		81.7	81.7	81.7	81.7	81.7	81.7					
Ckt #2 Amps			1.	.80	.80	.65	.8	.65	.65	-				

HP/PCM MODULAR HEAT SINK SYSTEM TEST, TRANSIENT, REFLUX MODE, 80 WATTS (Sheet 1 of 2)

E.4

Reflux Boiler Mode, Transient	T/C	Steady State	Time (Minutes) 0	5	10	20	40	50	55	60
Sink Tem (°F)		110	207							207
Q (Watts)		80								80
Htr Plate	1	130			134	134.5	137	140	144	148.5
	2	130			134	134.5	137	140	144	148.5
Evaporator										
Wall	3	124			128	129.5	132	134	139	143
	4	125			129	130.	132	135	140	144
Flange	5	128			132	132	135.5	138.5	143.5	148
	6	128			133	132	135.5	139	143.5	148
Adiabatic	7	124			128	129	131	134.5	139.	144
PCM	8	124			127	128	131	134	139	143
	9	123			126.5	128	130	134	138	143
	10				125.5	126	128	133	138.	142
	11				126	128	130	134	138.5	143
	12				126.5	127.5	130	134	138	142.5
	13				126	127.5	129.5	132	137	141.
	14				125	126	127	132.5	137	141.
	15				126	127	128	132.5	137	141.
	16				126	127	128	130.5	136	140
	17				-	-	-	-	-	-
	18				125	126	126.5	128	133	140
	19	123			126	127	128	130.5	136	140.5
Adiabatic	20	123.5			128	129	131	134.5	139.5	142.
Condenser										
Wall	21	123			126	128	130	133	138	142.
	22	122			125	126	128	132	137	141.5
Flange	23	121			126	127	129	132	137.5	142.
	24	124			124	126	128	131	135	139.5

HP/PCM MODULAR HEAT SINK SYSTEM TEST, TRANSIENT, REFLUX MODE, 80 WATTS (Sheet 2 of 2)

E.4

Reflux Boiler Mode	T/C	Steady State	Time (Minutes) 0	5	10	20	40	50	55	60				
Sink Temp (°F)		110	207							207				
Q (Watts)		80								80				
Diode Evap.														
Flange	25	122			128	128	132	134	138	143.5				
	26	122			128	128	132	134	138	143.5				
Wall	27	120			128	128	132	134.5	138	143.5				
	28	120			128	128.5	132	134.5	138	143.5				
Adiabatic	29	120			129	131.5	134	137	139.5	143.5				
	30	119			176	184.	185	186	187.	188				
Diode Cond														
Wall	31	118			182	189	190	191	192	193				
	33	117			187	195	194.5	195.5	196.5	197				
Flange	32	115			183	190	190.5	191.0	193	194				
	34	114			187	195	194.5	195.5	196.5	197				
Reservoir	35	117			187	196.5	195	196.5	197.5	197				
	36	116			189	197.5	196	197	198	199				
Sink Temp														
Inlet	39	86			92	94	96	96	97	-				
Outlet	40	106			127	132	137	139	140	-				
Flange	37	114			184	192	192	192.5	194.	195				
Heater Power														
Ckt #1 Volts		21.5			21.5	21.5	21.5	21.5	21.5	21.5				
Amps		3.8			3.8	3.8	3.8	3.8	3.8	3.8				
Watts		81.7			81.7	81.7	81.7	81.7	81.7	81.7				
Ckt #2 Volts														
Amps		.8 (ss)			.7	.60	.65	.65	.65	.65				
Watts														

Appendix F

RADIATING PANEL FEEDER HP NO. 1 BENCH TEST DATA

FEEDER HP NO. 1 BENCH TEST DATA, STRAIGHT CONFIGURATION, PREVIBRATION

F.1

Power In (Watts)	Tilt (in.)	Bath Temp	TC#1	TC#2	TC#3	TC#4	TC#5	TC#6	TC#7	TC#8	TC#9	TC#10
27.6	0.5	57	60.5	59	60.5	59	58	58	58	58	58	58
148.4	0.5	58	70	69.5	74	65	62	62.5	63	63	63.5	63
175.1	0.5	58	73.5	73	79	68.5	64	64.5	64.5	65	63.5	64
200.9	0.5	59	77.5	77.5	84.5	72	66.5	67	67.5	66.5	66	66
227.0	0.5	59	80	79.5	88	73	66.5	68	68	67	66	67
26.6	1.0	56	62	60	60.5	58.5	58	57.5	57.5	57.5	57.5	57.5
49.9	1.0	56.5	65	63	64	61	59.5	59.5	59	58.5	58.5	58.5
76.2	1.0	56	68.5	63	65.5	61	59.5	59	59.5	59	59	59
101.6	1.0	54.5	68.5	64.5	67	61.5	59	59	59	59.5	59	58.5
124.6	1.0	55	72	67.5	71	64	60	61	61	60.5	60	60
152.3	1.0	54	75	69.5	74	65.5	60	62	62	61	61	60.5
50.3	0.25	54.5	66	60	62	58	56.5	57	57	57	57	57
107.4	0.25	55	64.5	68	61.5	59	59.5	59.5	59.5	59.5	59.5	59
160.7	0.25	55.5	86.5	71	76	66	62	63	63	63	63	62.5
210.6	0.25	56.5	96	77	83.5	71	65	66.5	67	67	67	66.5
236.3	0.25	57.5	100	81	88.5	74.5	67	68.5	69	69	69	67.5
262.4	0.25	57	98	82.5	91	75	67	68.5	69	67.5	66.5	67
286.9	0.25	57	100	87	95.5	78	70	71	71	71	71	70
28.2	1.5	57	63	59.5	60.5	59	58	58	58	58	58	57.5
49.9	1.5	57.5	66	61	62	60	59	59	59	59	59	57.5
73.8	1.5	57	70	63	65.5	61	59	59.5	59.5	59.5	59	57.5
100.1	1.5	57.5	76	65.5	69	63	60.5	61	61	60.5	60.5	58.5
122.0	1.5	58	81	68	72	65	62	62	62.5	62	61.5	58.5
28.8	2.	56.5	62	60	61	59	58	58.5	58	57	56	56.5
33.8	2.	56	61.5	59.5	61	59	57.5	58	57.5	57	56	56
38.5	2.	56	63	61	62.5	60.5	58.5	59.5	58	57	56	56
42.9	2.	57	63	61	63	60.5	59	59.5	59	58	57	57
47.0	2.	57.5	64	62	64	61	59	60	59.5	59	57.5	57.5
52.8	2.	57.5	65	63	64.5	62	59.5	60.5	60	59.5	57.8	57.5
56.8	2.	58	66	65	65.5	62.5	60.5	61	60.5	60	58	58
64.3	2.	58	66.5	64	66	63	60.5	61.5	61	60.5	58	58
74.9	2.	58	68	65	67.5	63.5	61	62.5	61	61	58	58

FEEDER HP NO. 1 BENCH TEST DATA, L-SHAPED CONFIGURATION, PREVIBRATION

F.2

Power Input (Watts)	Tilt (in.)	Bath Temp (12)	TC#1	TC#2	TC#3	TC#4	TC#5	TC#6	TC#7	TC#8	TC#9	TC#10
27.4	½"	56.5	60	61.5	62.5	58.5	57.5	57.5	58	58	58	58
51.0	½"	57	63	65.5	69	61.5	60	60	60.5	60.5	60.5	60.5
100.0	½"	56	66.5	72.5	77	63.5	60.5	61	61.5	62	62	62
150.2	½"	55	71	81	89	67	60.5	63	64	64	64	64
175.0	½"	56.5	74.5	87	97	71	65	66.5	67.5	67.5	67.5	67.5
200.0	½"	57	78	93	105.5	73.5	76.5	78.5	80	80	80	80
225.0	½"	56.5	81.5	99	113.5	76	65	71	72	72	72	72
74.9	¼"	56.5	75	80.5	84	61	59.5	60	60.5	60.5	60.5	60.5
150.0	¼"	58.5	73	85	93.5	67	63	64	65	65	65	65
199.8	¼"	57	79.5	95	105.5	70	65	66.5	67.5	67.5	67.5	67.5
249.9	¼"	60.5	88	108	123	76	69.5	72	73	72.5	73	73
274.9	¼"	59	90	114.5	132.5	76.5	69/5	72	73	73	73	73
299.9	¼"	59.5	90.5	123	141	78.5	72	74	75	74.5	75	75
49.9	1"	59.5	63	67	70	60.5	58	60	60	60	59.5	60
100.7	1"	61	69	77.5	81.5	64.5	60	63	63	63	63	63
150.6	1"	62	75.5	89	95.5	68.5	63	67	67	67	66.5	66.5
174.7	1"	63	80	95	103.5	71	64.5	69.5	69.5	69.5	68.5	69
199.7	1"	63.5	83.5	101	111.5	73	65	71	71	71	70.5	70.5
224.8	1"	63.5	88.5	106	119.5	74.5	66.5	72	72	72	71	71.5
49.9	1.5"	56	62	64	64.5	58	56	58	58	58	57	56
761.8	1.5"	55	63.5	68.5	71.5	59	56	58	58	58	57.5	55
24.9	20"	58	59.5	61.5	63	57.5	56	57	57	57	56.5	56
49.8	2.0"	58	62	65	67	58.5	56	57	58	58	56.5	56
74.8	2.0"	58.5	84*	69	72.5	60	51.5	58.5	59.5	59	57	57

FEEDER HP NO. 1 BENCH TEST DATA, L-SHAPED CONFIGURATION, POSTVIBRATION

F.3

Power Input (Watts)	Tilt (in.)	Bath Temp. #12	TC#1 (on-Htr)	TC#2	TC#3	TC#4	TC#5	TC#6	TC#7	TC#8	TC#9	TC#10
0	½	55.0	59.0	59.0	59.5	58.4	57.0	57.0	57.0	57.0	57-	57
19.48	½	56.0	62.0	61.9	61.8	59.0	58.0	58.0	58.0	56	56	56
36.46	½	55.8	65.5	63.9	63.0	59.0	58.5	58.5	58.5	58.5	55.9	55.9
53.47	½	55.8	70.5	66.5	65.9	60.0	60.0	60.0	59.0	60.0	56.0	56.0
60.68	½	56.0	72.0	67.9	66.4	60.5	60.0	60.0	60.0	60.0	56.0	56.0
100.80	½	55.8	85.0	75.0	73.0	62.0	62.0	67.0	62.0	62.0	55.8	55.8
36.9	0	55	57	57	57	61	55	55	55	55	55	55
37.4	0	56	74	68	63	62	57.5	57.5	57.5	56	55.5	55.5
53.	0	56	83	74	66	63	58	58	58	58	56	56
91	0	56	103	85	72	64	60	60	60	60	56	60
18.86	½	55.5	70	62.5	60	62	56.5	56	55	52	55.5	55.5
56.60	½	57.5	91	75	66.5	63.8	59.0	59.	58.0	56.5	56	56.0
19.74	1"	56	70	63	60.5	62.5	57	56.5	56.5	56.5	56.5	56.5
49.58	1"	57	85.5	71	65.0	63.8	58.5	59.0	57.0	56.0	56.0	56.0
60.68	1"	58	91.0	74.5	66.5	64.0	59.0	59.0	59.0	56.5	56.5	56.5
110	1"	58	126	93	75	66	62	62	62	57	57	57

Appendix G

HP RADIATING PANEL ANALYSIS PROGRAM LISTING

```
// JOB T
// FOR
*ONE WORD INTEGERS
*EXTENDED PRECISION
*IOCS(CARD,1132 PRINTER,KEYBOARD,TYPEWRITER)
  222 READ (2,100) TIN, CPM, HFLU, AWALL, HINT1, AINT1, HINT2, AINT2      RAD00010
      READ (2,100) HEVAP, AEVAP, HCOND, ACOND, HPOLY, APOLY              RAD00020
      READ (2,100) APANL, EPS, EPSK, EPSB, TSINK, TROOT, ETA
  100 FORMAT (8F10.5)                                                     RAD00040
      TSTOR=TIN
  221 WRITE (3,106)                                                       RAD00050
  106 FORMAT (1H1,25X,'STUDY OF HEAT PIPE RADIATING PANEL',///)
      TIN=TSTOR
      WRITE (3,107)TIN, CPM, HFLU, AWALL, HINT1, AINT1                   RAD00070
  107 FORMAT (5X,'TIN =',8X,'CPM =',7X,'HFLU =',6X,'AWALL =',6X,'HINT1 =
     A',6X,'AINT1 =',/,6X,6(3X,F10.3))
      WRITE (3,108) HINT2, AINT2, HEVAP, AEVAP, HCOND, ACOND
  108 FORMAT (5X,'HINT2 =',6X,'AINT2 =',6X,'HEVAP =',6X,'AEVAP =',6X,'HC
     BOND =',6X,'ACOND =',/,6X,6(3X,F10.3))
      WRITE (3,113) HPOLY, APOLY, APANL, EPS, EPSK, EPSB
  113 FORMAT (5X,'HPOLY =',6X,'APOLY =',6X,'APANL =',6X,'EPS =',6X,2X,
     C'EPSK =',7X,'EPSB =',/,6X,6(3X,F10.3))
      WRITE (3,114) TSINK, TROOT, ETA
  114 FORMAT (5X,'TSINK =',6X,'TSTART =',6X,'ETA =',/,6X,3(3X,F10.3))
      C1=CPM*(1.-EXP(-1.*HFLU*AWALL/CPM))                                 RAD00120
      UA1=1./(1./(HINT1*AINT1)+1./(HINT2*AINT2)+1./(HEVAP*AEVAP)         RAD00130
     1+1./(HCOND*ACOND)+1./(HPOLY*APOLY))                                 RAD00140
      QSUM=0.0                                                            RAD00150
      QSUML=0.0                                                           RAD00160
      I=0                                                                 RAD00170
      K=1                                                                 RAD00180
    1 F=5.67E-8*APANL*(EPS*ETA*(TROOT**4-TSINK**4)+EPSK*(TROOT**4-(EPSK*
     1TROOT**4+EPSB*TSINK**4)/(EPSB+EPSK)))-C1*(TIN-(UA1*TROOT+C1*
     2TIN)/(UA1+C1))                                                      RAD00210
      I=I+1                                                               RAD00220
      IF (ABS(F)-.001) 200,5,5
    5 IF (I-100) 10,50,50                                                 RAD00240
   10 DFDT=5.67E-8*APANL*4.*(EPS*ETA+EPSK-(EPSK**2)/(EPSB+EPSK))
     1*TROOT**3+C1*UA1/(C1+UA1)
      TROOT=TROOT-F/DFDT                                                  RAD00270
      GO TO 1                                                             RAD00280
   50 WRITE (3,101)
  101 FORMAT (5X,'FAILED TO CONVERGE AFTER 100 ITERATIONS')
      GO TO 250
  200 TBAK4=(EPSK*TROOT**4+EPSB*TSINK**4)/(EPSB+EPSK)
      QIN=5.67E-8*APANL*(EPS*ETA*(TROOT**4-TSINK**4)+EPSK*(TROOT**4-TBAK
     A4))
      QLEAK=5.67E-8*APANL*EPSK*(TROOT**4-TBAK4)
      TBACK=TBAK4**.25
      TCOND=QIN/(HPOLY*APOLY)+TROOT
      TVAP=QIN/(HCOND*ACOND)+TCOND
      TEVAP=QIN/(HEVAP*AEVAP)+TVAP
      TBLOK=QIN/(HINT2*AINT2)+TEVAP
      TWALL=QIN/(HINT1*AINT1)+TBLOK
      TOUT=TIN-QIN/CPM
      QSUM=QSUM+QIN                                                       RAD00010
      QSUML=QSUML+QLEAK                                                   RAD00020
      WRITE (3,109) K, TIN, TOUT, QIN, QLEAK                             RAD00030
  109 FORMAT(1H0,'FOR PANEL SEGMENT NO. ',I2,', TIN= ',F10.3,' TOUT= ',FRAD00040
     110.3,' QIN= ',F10.3,' QLEAK= ',F10.3)                              RAD00050
      WRITE (3,110) TCOND, TVAP, TEVAP, TBLOK, TWALL                     RAD00060
  110 FORMAT (8X,'TCOND',8X,'TVAP',8X,'TEVAP',8X,'TBLOK',8X,'TWALL',/,   RAD00070
     15X,5(F10.3,3X))
      TCONF=1.80*TCOND-459.67
      TVAF=1.80*TVAP-459.67
      TEVPF=1.80*TEVAP-459.67
      TBLKF=1.80*TBLOK-459.67
      TWALF=1.80*TWALL-459.67
      TRTF=1.80*TROOT-459.67
      TBKF=1.80*TBACK-459.67
      WRITE (3,115) TCONF,TVAF, TEVPF, TBLKF, TWALF
```

```
  115 FORMAT (1X,5X,5(F10.3,3X))
      WRITE (3,112)TROOT, TBACK, TRTF, TBKF
  112 FORMAT (9X,'SEGMENT ROOT TEMP = ',F10.3,' DEG K, AND BACK TEMP = '
     1,F10.3,' DEG K',/,27X,'= ',F10.3,' DEG F',16X,'= ',F10.3,' DEG F',
     2/)
      IF (K-6) 55,53,53                                                  RAD00090
   53 WRITE (3,111) QSUM, QSUML                                          RAD00100
  111 FORMAT(1H0,'TOTAL HEAT INTO SYSTEM = ',F10.3,' WATTS AND TOTAL LEARAD00110
     1K THRU BACK = ',F10.3,' WATTS.')                                   RAD00120
      GO TO 250                                                          RAD00130
   55 K=K+1                                                              RAD00140
      TIN=TOUT                                                           RAD00150
      GO TO 1                                                            RAD00160
  250 WRITE (1,102)                                                      RAD00170
  102 FORMAT (2X,'READY FOR NEW INPUT DATA')                             RAD00180
  251 READ (6,103)NPAR                                                   RAD00190
  103 FORMAT (I3)                                                        RAD00200
      IF (NPAR-24) 40,40,41
   41 WRITE (1,104)                                                      RAD00220
  104 FORMAT (2X,'INVALID PARAMETER NUMBER.  TRY AGAIN.')                RAD00230
      GO TO 251                                                          RAD00240
   40 GO TO (201,202,203,204,205,206,207,208,209,210,211,212,213,214,    RAD00250
     1215,216,217,218,219,220,221,222,223,224), NPAR
  201 READ (6,105) TSTOR
  105 FORMAT (F10.5)                                                     RAD00280
      GO TO 251                                                          RAD00290
  202 READ (6,105) CPM                                                   RAD00300
      GO TO 251                                                          RAD00310
  203 READ (6,105) HFLU                                                  RAD00320
      GO TO 251                                                          RAD00330
  204 READ (6,105) AWALL                                                 RAD00340
      GO TO 251                                                          RAD00350
  205 READ (6,105) HINT1                                                 RAD00360
      GO TO 251                                                          RAD00370
  206 READ (6,105) AINT1                                                 RAD00380
      GO TO 251                                                          RAD00390
  207 READ ( 6,105) HINT2                                                RAD00400
      GO TO 251                                                          RAD00410
  208 READ (6,105) AINT2                                                 RAD00420
      GO TO 251                                                          RAD00430
  209 READ (6,105) HEVAP                                                 RAD00440
      GO TO 251                                                          RAD00450
  210 READ (6,105)AEVAP                                                  RAD00460
      GO TO 251                                                          RAD00470
  211 READ (6,105) HCOND                                                 RAD00480
      GO TO 251                                                          RAD00490
  212 READ (6,105) ACOND                                                 RAD00500
      GO TO 251                                                          RAD00510
  213 READ (6,105) HPOLY                                                 RAD00520
      GO TO 251                                                          RAD00530
  214 READ (6,105) APOLY                                                 RAD00540
      GO TO 251                                                          RAD00550
  215 READ (6,105) APANL                                                 RAD00560
      GO TO 251                                                          RAD00570
  216 READ (6,105) FPS                                                   RAD00580
      GO TO 251                                                          RAD00590
  217 READ (6,105) EPSK
      GO TO 251                                                          RAD00610
  218 READ (6,105) EPSB                                                  RAD00620
      GO TO 251                                                          RAD00630
  219 READ (6,105) TSINK                                                 RAD00640
      GO TO 251                                                          RAD00650
  220 READ (6,105) TROOT                                                 RAD00660
      GO TO 251                                                          RAD00670
  224 READ (6,105) ETA
      GO TO 251
  223 CALL EXIT                                                          RAD00680
      END                                                                RAD00690
// XEQ
```

RADIATING PANEL PARAMETER LISTING

Code	Parameter	Code	Parameter
001	T_{inlet} (°K)	013	$h_{polyurethane}$
002	MC_p (W/°K)	014	$Area_{polyurethane}$
003	h_{fluid} (W/m^2 °K)	015	$Area_{panel\ segment}$
004	$Area_{wall\ of\ pipe}$ (m^2)	016	$\epsilon \times \epsilon_{sink}$
005	$h_{interfaces}$	017	$\epsilon_{effective}$
006	$Area_{interface\ 1}$	018	$\epsilon_{backface} \times \epsilon_{sink}$
007	$h_{interface\ 2}$	019	T_{sink}
008	$Area_{interface\ 2}$	020	T_{Root} ~ guess to start iterative process
009	$h_{evaporator}$	021	Re-Compute
010	$Area_{evaporator}$	022	Re-read; then compute
011	$h_{condenser}$	023	EXIT
012	$Area_{condenser}$	024	η_f

Note: All areas except panel area are
<u>effective</u> areas, not actual area.
η_f at 024 takes care of panel area.

Appendix H

HP RADIATING PANEL SYSTEM TEST DATA

HP RADIATING PANEL SYSTEM TEST DATA, TESTS 1-13 (Sheet 1 of 2)

Test # →		1	2	3	4	5	6	7	8	9	10	11	12	13
(Nom) Cold Wall Temp. (°F)		-40	-40	-40	-40	-40	-40	-40	-40	-40	-20	-20	-20	-20
Actual Cold Wall Temp.		-40	-40	-40	-40	-40	-40	-40	-40	-40	-20	-20	-20	-20
(Nom) Flow Rate (GPM)		.40	.40	.4	.80	.80	.80	1.20	1.20	1.20	.40	.40	.40	.80
Actual Flow Rate		.40	.40	.40	.80	.80	.80	1.20	1.20	1.20	.40	.40	.40	.80
(Nom) Inlet Temp.		30	60	90	30	60	90	30	60	90	30	60	90	30
TC #	1	31.0	59.	88.	31.0	59.	88.	30.	58.	62.	30.5	60.	88.	29.
	2	7.0	20.	40.	9.0	26.	44.	10.	27.	47.	13.	28.5	47.	13.
	3	7.0	20.	40.	9.0	26.	44.	10.	27.	47.	13.	28.5	47.	13.
	4	7.0	20.	40.	8.5	26.	43.5	10.	27.	47.	13.	28.5	47.	13.
(1)	5	5.0	18.	36.5	7.0	23.5	40.5	8.	25.	43.5	11.5	27.	44.5	11.5
	6	4.5	17.5	36.	7.	23.5	40.	8.	24.	43.	11.5	25.5	43.5	11.5
	7	3.0	16.	34.	5.	21.	37.5	6.	22.	40.5	10.	24.	41.5	10.5
	8	-17.0	-4.5	13.	-17.	1.	20.5	-14.	4.	24.	-6.	7.	23.	-7.
	9	17.5	36.	61.	20.5	43.5	66.5	22.	44.	69.	21.	42.	66.	22.
	10	-1.	10.	28.5	1.	16.	31.5	2.	17.	34.5	7.	20.5	37.	7.
(2)	11	-1.	10.	28.	1.	15.	31.	2.	17.	33.5	7.	20.5	37.	7.
	12	-3.	7.	23.5	-1.5	12.	27.	0.	14.	29.5	5.5	17.5	33.5	5.
	13	-3.	7.	24.	-1.5	12.5	27.5	0.	14.	30.	5.5	18.	34.5	5.
	14	13.	30.5	56.	17.5	39.	61.	19.	41.	64.	17.5	37.5	61.	19.
	15	-3.	8.	25.	0.	13.	27.	2.5	14.5	30.	5.	17.	34.	5.
(3)	16	-4.	7.	25.	-3.5	12.	27.	-2.	14.	30.	5.	17.	33.5	5.
	17	-5.	5.5	23.	-5.	11.	25.	-3.	12.	27.5	4.	16.	33.	4.5
	18	-5.5	5.	22.	-5.	10.	24.	-4.	11.5	26.5	3.5	15.	31.	4.
	19	10.5	26.5	51.5	14.5	35.	56.	17.	37.5	59.5	15.	33.5	57.	17.
	20	-2.5	8.	26.	-.5	13.5	27.5	1.	15.	30.	6.	18.	35.	6.5
	21	-2.5	8.	26.	-.5	13.5	27.5	1.	15.	30.	5.5	18.	35.	6.
(4)	22	-2.5	8.5	26.	-.5	13.5	27.5	1.	15.	30.	6.	18.5	35.	7.
	23	-3.	6.	24.	-2.	11.5	25.5	0.	13.	28.	5.	16.5	33.	5.5
	24	-3.5	6.	24.	-2.	11.5	25.	0.	13.	28.	5.	16.5	33.	5.5
	25	-6.	3.5	20.	-5.	8.5	22.	-3.	10.	24.	3.5	13.5	29.	3.
	26	-18.5	-10.	7.	-20.	-4.5	9.5	-17.	-3.	12.5	-7.5	1.5	19.5	-8.
	27	8.5	24.5	49.	12.	32.	52.	14.	34.	55.	14.	31.5	54.5	15.
	28	-7.	4.	21.	-7.	8.	22.	-4.	10.	24.	2.	13.5	30.	2.
(5)	29	-7.	2.	20.5	-7.	6.5	21.	-4.5	9.	23.	2.	13.5	30.	2.5
	30	-8.	1.	18.	-8.	5.5	19.5	-6.	8.	22.	1.5	12.5	28.5	1.5

HP RADIATING PANEL SYSTEM TEST DATA, TESTS 1-13 (Sheet 2 of 2)

H.1 (Cont.) Test #	1	2	3	4	5	6	7	8	9	10	11	12	13
(5) TC # 31	-9.	-1.	16.5	-9.5	4.	17.5	-7.	6.	19.5	.5	11.	27.	.5
32	6.5	22.	46.	10.	28.5	48.5	12.	31.	51.5	12.	28.5	52.	12.5
33	-8.	2.	21.	-7.	6.	20.5	-5.	8.	23.	2.	13.	29.5	2.5
34	-8.	1.5	18.	-7.	5.	18.5	-5.	7.	20.	1.5	12.	28.5	1.5
(6) 35	-9.	0.	16.	-8.5	4.	16.	-6.5	6.	18.	.5	10.5	26.	.5
36	-9.5	0.	15.5	-9.	3.5	15.5	-6.5	5.	17.	.5	10.5	25.5	.5
37	-20.5	-13.	7.	-21.	-8.0	10.5	-19.	-6.	12.	-9.	1.	21.	-9.5
38	-14.5	-8.	6.	-15.	-4.	6.5	-13.	-3.	8.	-3.	5.	17.	-3.5
39	-14.0	-7.	7.	-14.	-3.	7.	-12.	-2.	9.	-3.	5.	18.	-3.5
40	-18.5	-12.	1.	-20.	-8.	2.5	-18.	-7.	4.	-7.	1.	13.5	-7.
41	-12.	-5.5	9.	-13.	-1.5	9.5	-11.	0.	12.	-2.5	6.5	19.5	-2.
42	-11.5	-4.	10.	-12.	0.	11.	-10.	2.	13.	-1.5	7.5	20.5	-1.5
43	-10.5	-3.	12.	-10.	1.	12.5	-9.	2.5	15.	-.5	8.5	21.	-.5
44	-12.5	-5.	9.	-13.	-1.	11.	-11.	1.	13.5	-2.5	7.	19.5	-2.
45	-10.5	-2.	12.	-10.	2.	14.	-9.	4.	16.	-.5	9.	22.	-.5
46	-7.5	1.	15.	-6.	6.	19.	-5.	7.5	21.	2.	12.5	26.	2.
47	-5.5	4.	18.	-5.5	8.	20.	-4.	9.5	22.5	3.	14.	27.	3.
48	13.5	34.	64.	15.	37.5	61.	16.	38.	61.5	17.	39.5	66.	17.5
Immersion T/C Inlet	30.	59.	90.	32.	60.	90.	30.	60.	90.	30.	60.	91.	30.
Strap on T/C's Inlet	38.	59.	90.		60.	90.	33.	60.	90.	35.	60.	89.	32.
Outlet	34.	58.	83.			86.	32.	61.	86.	34.	59.	84.	31.
$T_{in}-T_{out}$	4.	1.	7.			4.	1.	1.	4.	1.	1.	5.	1.
DVM Millivolts	.0122	.0506	.1400	.0308	.0562	.077	.080	.0482	.0572	.019	.036	.100	.025
ΔT (^{o}F)	.55	2.3	6.35	1.4	2.55	3.5	3.65	2.2	2.6	.85	1.65	4.55	1.15
$mCp\,\Delta T$ = Q (watts)	12.	50.	140.	61.	120.	160.	245.	150.	175.	19.	36.	100.	51.

HP RADIATING PANEL SYSTEM TEST DATA, TESTS 14-27 (Sheet 1 of 2)

H.2	Test # →	14	15	16	17	18	19	20	21	22	23	24	25	26	27
(Nom)Cold Wall Temp.		-20	-20	-20	-20	-20	0	0	0	0	0	0	0	0	0
Actual Cold Wall Temp.		-20	-20	-20	-20	-20	0	0	0	0	0	0	0	0	0
(Nom)Flow Rate (GPM)		.8	.8	1.2	1.2	1.2	.4	.4	.4	.8	.8	.8	1.2	1.2	1.2
Actual Flow Rate		.8	.8	1.2	1.2	1.2	.4	.4	.4	.8	.8	.8	1.2	1.2	1.2
(Nom)Inlet Temp.		60	90	30	60	90	30	60	90	30	60	90	30	60	90
TC #	1	57.	86.5	30.	58.	88.	35.	60.	90.	33.5	60.	89.	28.	57.	88.5
	2	31.5	49.	15.	33.5	52.	23.	35.	53.5	22.5	40.	57.	19.5	39.5	59.
	3	31.5	49.	15.	33.5	52.	23.	35.	53.5	22.5	40.	57.5	19.5	40.5	59.
(1)	4	31.5	49.	15.	33.5	52.	23.	35.	53.5	22.5	40.	57.	19.5	40.	59.
	5	29.5	46.	13.5	31.5	49.	22.	33.5	51.	21.	38.	55.	19.	38.5	56.5
	6	28.5	45.5	13.	30.5	48.5	22.	33.5	50.5	21.	38.	54.5	19.	37.5	56.
	7	27.	43.	12.5	28.5	45.5	21.	32.	48.5	20.5	36.5	52.	18.	36.	53.5
	8	9.	25.5	-6.	11.5	28.5	-7.5	14.5	31.5	7.	18.	36.	5.5	18.	38.
	9	45.	68.5	23.5	47.	71.	29.	45.5	69.5	28.5	50.5	74.	25.	50.	76.
	10	23.5	38.5	9.	25.5	41.	18.	28.5	45.	18.	33.	48.5	15.5	33.	49.5
	11	23.5	38.5	8.5	25.	41.	18.	28.5	45.	17.5	33.	48.	15.5	33.	49.5
(2)	12	20.5	34.5	7.	22.5	36.5	17.	26.5	41.5	16.5	31.	45.	14.5	31.	46.5
	13	21.5	35.	7.	22.5	38.	17.	26.5	41.5	16.5	31.	45.	14.5	31.5	46.5
	14	41.5	63.	21.	44.	66.5	26.5	41.5	65.	26.5	47.	69.	23.5	47.5	71.
	15	20.5	34.5	7.	22.	37.	17.	26.5	42.	16.5	30.	45.	15.	31.	45.5
(3)	16	20.5	34.	7.	21.5	37.	17.	25.5	42.	16.5	30.	45.	14.5	31.	45.5
	17	19.	33.	6.	20.5	35.	16	25.	40.5	15.5	29.	43.5	14.	30.	45.
	18	18.5	31.5	5.	19.5	33.5	15.5	25.	39.5	15.5	28.5	42.	13.5	29.	43.
	19	37.5	58.5	19.	41.	62.	24.5	39.	62.5	25.	44.	65.5	22.	45.	67.5
	20	21.	34.5	8.5	22.5	37.	17.5	26.5	43.5	17.	31.	45.	15.5	31.5	46.
	21	21.	34.5	8.5	22.5	37.	17.5	27.	43.	17.	31.	45.	15.5	31.5	46.
	22	25.	34.5	8.5	22.5	37.	17.5	26.5	43.	17.	30.5	45.	15.5	31.5	46.
(4)	23	19.	33.	7.	21.	35.	16.5	25.5	41.	16.5	29.	43.	15.	30.	44.5
	24	19.5	32.5	7.	21.	34.5	16.5	25.5	41.	16.5	29.	43.	15.	30.	44.5
	25	16.5	28.5	5.	18.5	31.5	15.	23.	37.5	16.	27.	40.	13.	27.	40.5
	26	4.5	19.5	-7.5	5.5	23.	+6.	13.5	28.5	6.5	17.	31.5	5.	18.	33.
	27	35.	55.5	17.5	38.5	32.	23.5	36.5	59.	24.	42.	62.5	21.	42.	64.
	28	16.5	29.5	4.	18.	32.	14.5	22.5	38.5	15.	26.5	40.	12.5	26.5	41.
(5)	29	16.5	29.5	4.	18.	30.5	14.5	22.5	38.5	15.	26.5	40.5	12.5	26.5	41.
	30	15.	28.	3.	16.5	29.	14.	22.	36.5	14.	26.	39.	12.5	25.	40.

HP RADIATING PANEL SYSTEM TEST DATA, TESTS 14-27 (Sheet 2 of 2)

H.2 (Cont.) Test #		14	15	16	17	18	19	20	21	22	23	24	25	26	27
(5) TC #	31	14.	26.5	2.5	15.5	29.	13.	21.	35.5	13.5	25.	37.5	11.5	25.5	38.5
	32	32.	52.	15.	35.5	55.	21.5	34.	56.5	22.5	39.5	59.	19.5	40.5	61.
	33	15.	28.5	4.	16.5	30.5	14.5	23.	37.5	15.	26.	39.	13.	26.5	40.
	34	15.	27.	3.	16.	29.	13.5	21.5	36.	14.5	25.	38.5	12.5	25.5	39.
(6)	35	13.	25.	2.5	14.5	27.	13.	20.	34.5	13.5	23.5	36.	11.5	24.5	37.
	36	13.	25.	2.	14.5	27.	13.	20.	34.5	13.5	23.5	36.	11.5	24.	36.5
	37	4.5	20.5	-8.5	7.	22.5	5.	12.	29.	6.	15.	31.	4.	16.5	32.5
	38	6.5	16.5	-3.	7.5	18.5	10.	15.5	27.	10.5	18.5	29.	8.5	19.5	29.
	39	7.5	17.5	-2.5	8.5	19.	10.5	16.	28.	10.5	18.5	29.5	9.	19.5	30.
	40	3.	13.5	-6.	4.	15.5	7.	13.	24.5	7.5	16.	26.5	6.	17.	36.5
	41	8.5	19.5	-1.5	10.	21.5	11.5	17.	29.	11.	20.	31.5	10.	21.	31.5
	42	9.5	20.5	-.5	11.	22.5	11.5	17.5	29.5	11.5	21.	32.5	10.	21.5	32.5
	43	10.5	22.0	.5	11.5	24.	12.	19.	30.5	12.	22.	33.	10.5	22.	34.
	44	9.	20.5	-1.	11.	22.5	10.5	17.5	29.	10.5	21.	32.5	9.5	21.	33.
	45	11.5	22.5	1.	13.	25.	12.	19.5	30.5	12.	22.	34.5	10.5	22.5	35.
	46	14.	26.5	3.	15.5	29.	14.5	22.	31.5	13.5	25.	37.5	12.	25.	38.5
	47	16.	28.5	4.5	17.5	31.	15.	24.	37.	15.	27.	39.	13.	27.	40.
	48	39.	62.5	19.5	41.	63.5	25.	43.	70.5	25.	45.	68.5	22.	44.5	69.
Immersion T/C in		60	90	30	60	89	33	60	92	32	60	92	29	59	90
Strap on T/C in		61	88	31	61	87	40	60	90	36	60	89	30	60	89
out		57	83	30	60	83	38	59	84	34	59	86	31	59	87
$T_{in} - T_{out}$		4	5	1	1	4	2	1	6	2	1	3	1	1	
DVM Millivolts		.048	.072	.034	.047	.047	.025	.042	.110	.026	.042	.061	.030	.038	.040
ΔT (°F)		2.2	3.25	1.55	2.15	2.15	1.15	1.9	5.0	1.2	1.9	2.75	1.35	1.75	1.85
$mCp\,\Delta T = Q$ (watts)		100	145	110	145	145	25	45	110	54	83	123	90	120	125

HP RADIATING PANEL SYSTEM TEST DATA, RETESTS, REVERSE INLET AND OUTLET (Sheet 1 of 2)

H.3	Test # →	1	7	27	9	18	18R	15R	12R	27R	24R	21R
		Re-tests					Reverse Inlet & Outlet					
(Nom) Cold Wall Temp.		-40.	-40.	0.	-40.	-20.	-20.	-20.	-20.	0.	0.	0.
Actual Cold Wall Temp.		-40.	-40.	0.	-40.	-20.	-20.	-20.	-20.	0.	0.	0.
(Nom) Flow Rate (GPM)		.40	1.2	1.2	1.2	1.2	1.2	.80	.40	1.2	.80	.40
Actual Flow Rate		.40	1.2	1.2	1.2	1.2	1.2	.80	.40	1.2	.80	.40
(Nom) Inlet Temp.		30.	30.	90.	90.	90.	90.	90.	90.	90.	90.	90.
TC #	1	30.	28.	90.	90.5	88.5	56.	53.	56.	61.	60.	60.
	2	6.5	7.	60.5	49.	54.5	34.5	34.	34.	42.	43.	42.
	3	6.5	7.	60.5	49.	54.5	34.5	34.	34.	43.5	43.5	42.
(1)	4	6.5	7.	60.	49.	53.5	34.5	34.	34.	43.5	43.	42.
	5	4.5	5.	57.	45.5	51.	32.5	31.5	31.5	42.	42.	40.
	6	4.5	5.	57.	45.	50.5	32.5	31.	31.5	41.5	40.5	40.
	7	3.	3.	54.5	42.	48.	30.	29.5	29.5	40.	39.	38.5
	8	-18.	-18.5	39.	29.5	33.	10.	10.	11.	22.5	22.	21.
	9	17.5	17.5	77.	72.	73.5	56.	53.	51.	61.5	59.	57.
	10	-1.5	-.5	51.	37.	43.5	32.5	31.	30.5	42.	41.	39.5
(2)	11	-1.5	-.5	50.5	37.	43.5	32.5	31.	30.5	42.	41.	39.5
	12	-3.5	-3.	47.	31.5	39.	29.	28.	27.	39.	37.5	36.5
	13	-3.5	-3.	47.5	33.	40.	29.5	28.5	27.5	39.5	38.5	36.5
	14	13.	14.5	73.	66.5	69.	60.	57.	54.5	65.	63.	60.
	15	-4.	-3.	47.	31.	39.	34.5	33.	31.	44.	43.	41.
	16	-4.5	-3.	46.5	31.	39.	34.5	33.	31.	43.5	43.	41.
(3)	17	-5.5	-4.	45.5	29.	37.5	33.	31.	29.	42.	41.	39.
	18	-6.	-5.	44.	27.5	36.	31.5	30.	28.	41.	40.5	38.
	19	9.	11.5	69.	61.	64.5	62.	59.5	55.5	67.	64.5	61.5
	20	-3.	-1.5	46.5	30.5	38.5	40.	37.5	34.5	48.5	47.	44.5
	21	-3.	-1.5	46.5	31.	38.5	40.	37.5	34.5	48.	47.	44.5
	22	-3.	-1.5	46.5	30.5	38.5	40.	37.5	34.5	48.	46.5	44.5
(4)	23	-4.5	-3.	45.	28.5	36.5	37.5	35.5	32.5	46.5	45.	43.
	24	-4.5	-3.	45.	28.	36.	37.5	35.	32.5	46.	45.	42.
	25	-6.5	-6.	41.	23.5	31.5	33.	31.5	29.	42.	42.	39.
	26	-20.5	-21.	37.	17.5	29.	32.	30.	25.	40.	38.	34.5
	27	7.5	10.5	65.	56.5	60.	64.5	62.5	58.	68.5	66.5	64.
	28	-8.	-7.	41.	23.5	32.5	40.5	39.	34.5	48.5	47.5	44.5
(5)	29	-7.5	-7.	41.5	24.5	32.5	40.5	39.	34.5	48.5	47.5	45.
	30	-9.	-7.5	40.	22.	31.	38.5	37.	33.	47.	46.	43.5

HP RADIATING PANEL SYSTEM TEST DATA, RETESTS, REVERSE INLET AND OUTLET (Sheet 2 of 2)

H.3 (Cont.) Test # →	Re-tests						Reverse Inlet & Outlet						
	1	7	27	9	18		18R	15R	12R	27R	24R	21R	
(5) TC# 31	-10.	-9.	38.5	20.5	29.		37.	35.5	31.5	45.	44.	42.	
32	4.5	8.	62.	52.	56.5		72.	70.	65.	75.	73.	70.	
33	-8.	-7.	40.	25.	31.		47.5	44.	39.5	53.	57.5	49.	
34	-8.5	-7.	39.	21.	29.5		47.5	43.5	39.	53.	51.5	49.	
(6) 35	-10.	-9.	37.	19.	28.		42.	41.5	36.5	50.	49.	46.5	
36	-10.	-9.	36.5	18.	27.		42.	40.	36.	49.5	48.	45.5	
37	-22.5	-22.	32.5	8.5	20.0		40.	38.	34.	47.5	46.	42.	
38	-15.5	-15.	29.5	8.	18.5		27.5	26.5	23.5	37.5	36.5	35.	
39	-15.	-14.	30.	9.	19.		29.	27.	24.5	38.5	37.5	35.5	
40	-19.5	-19.5	27.5	4.5	16.		20.	19.	16.5	31.	30.	28.5	
41	-13.5	-13.	31.5	11.	21.		25.	24.	21.5	35.	32.5	33.	
42	-12.5	-11.5	32.5	13.	22.5		22.	21.	19.	32.5	32.	30.5	
43	-11.5	-11.	33.5	15.	23.5		23.5	22.	21.	34.	33.	31.5	
44	-13.5	-13.	33.	14.	23.		18.	17.	17.	29.5	29.	27.	
45	-11.	-10.	35.	16.5	25.5		20.5	19.5	19.	31.5	31.	29.5	
46	-8.	-7.5	38.5	22.	29.5		19.	18.5	19.	30.5	30.	29.	
47	-6.	-6.	41.	24.5	32.5		22.	20.5	20.5	33.	32.5	31.	
48	12.	12.5	69.5	63.5	65.		92.	93.	94.	91.5	92.5	93.	
Immersion Inlet	29.	29.	92.	92.	90.		88.	88.	86.	90.	91.	91.	
Strap On TC Inlet	32.	30.	91.	92.	89.		87.	86.	83.	88.	89.	86.	
Outlet	31.	29.	89.	89.	87		89.	89.	89.	90.	91.	91.	
$T_{in} - T_{out}$	1	1	2	3	2								
DVM Millivolts	.0154	.030	.044	.060	.0533		.046	.071	.136	.033	.062	.111	
T (^{o}F)	.7	1.35	2.0	2.75	2.40		2.1	3.25	6.2	1.50	2.80	5.05	
mCp T = Q (watts)	15.	90.	135.	182.	160.		140.	142.	140.	100.	125.	110.	
					$Q = f(T_P)$	=	110.5	107.	103.3	94.7	91.9	87.8	

Appendix I

HP AUGMENTED COLD RAIL BENCH TEST DATA

HP AUGMENTED COLD RAIL BENCH TEST DATA, PREVIBRATION, LIFE TEST RAIL

I.1														
Heat Input (Watts)		0	20	73	163	222	290	368	454	73	163	222	290	368
	T/C													
Evaporator	1	95	91	92	106	107	110	113	115	62	69	72	76	81
	2	95	91	92	106	107	110	113	115	62	67	70	73	78
Transport	3	95	90	90	102	102	103	104	105	57	61	63	68	68
Condenser	4	95	90	88	100	99	100	99	98	55	56	57	58	58
	5										55	56	56	56
	6										56	56	57	56
	7										55	55	55	55
	8	95	90	88	100	99	100	99	98	55	55	55	55	55
Vapor	11	95	91	91	103	103	106	108	110	62	67	70	73	80
Spray Bath	12	95	90	88	100	98	98	98	97	53	54	55	55	55

Note: TC 9&10 Off

HP AUGMENTED COLD RAIL BENCH TEST DATA, POSTVIBRATION, LIFE TEST RAIL

I.2												
Heat Input (Watts)			73	165.5	225	294	354	354	73.	165.5	225
Evaporator T/C	1	99	103.5	109	109	113	115	103	64	73	78
	2	99	103.5	109	109	113	115	103	63	71.5	77
Vapor	11	99	102	107	107	112	114	113	63	72.5	80
Transport T/C	3	99	101	104	103	105	106	93	59.5	64.5	68
Condenser T/C	4	99	100	101.5	100	100	100	85	56	58.5	60
	5		100	101.	99	99.5	99	81	55	57	58
	6		100	101.	99	99.5	99	79	53.5	55.	57
	7		99.5	100.5	98	98	97	77	53	53	54
	8	99	99	99	96	96	96	76	53	53	54
Spray Bath	12	99	99	99	95	95	94	76	53	53	54
Burn Out Data @ ½" Tilt		Watts	165.	225.	294.						
		Te	106	110	114						
		ΔTec	7.	11	17						

HP AUGMENTED COLD RAIL BENCH TEST DATA, SYSTEM TEST RAIL

I.3														
Heat Input (Watts)		15.5	62	140	190	249	15.5	62	140	249	315	389	471	560
	T/C													
Evaporator	1	66	68.5	71.5	73	75	99.5	100	102	105.5	107	109	111	114
	2	66	68.5	71.	72.5	74.5	99.5	100	102	105.5	107	109	111	114
Transport	3	65	66	67	67	68	99	99	100	102	102	103	104	106
	4	65	65	66	66	66.5	99	99	99.5	100	100.5	101	102	102
	5												102	102
	6												100	100
	7												101	102
	8	65	65	66	66	66.5	99	99	99.5	100	100.5	101	102	101
Vapor	11	66.5	69	71.5	72.5	75.5	98	99	100	104	105	108	110	113
Spray Bath	12	65	65	65	64.5	64.5	99	98	98.5	98.5	98	98	98	99

Appendix J

HP AUGMENTED COLD RAIL SYSTEM TEST DATA

HP AUGMENTED COLD RAIL SYSTEM TEST DATA, TESTS 1-13 (Sheet 1 of 2)

J.1 Test #:		1	2	3	4	5	6	7	8	9	10	11	12	13
Tinlet (Nominal)		70.	70.	70.	70.	70.	70.	80.	80.	80.	90.	90.	90.	70.
Flow Rate #/Hr														
(Nominal)		80.	80.	80.	80.	40.	40.	80.	80.	80.	80.	80.	80.	40.
Actual		80.	80.	80.	81.	40.	40.	80.	80.	80.	80.	80.	80.	40.
#of Flow Passages		2	2	2	2	2	2	2	2	2	2	2	2	1
Heater Circuit														
(Inlet side) #1 (Nom. Watts)		100	100.	100	100	100	100	100	100	100	100	100	100	100
Volts		31.2	31.2	31.2	30.15	30.15	30.15	30.15	30.15	30.15	30.15	30.15	30.15	30.15
Amps		3.25	3.25	3.25	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36
Watts		101.4	101.4	101.4	101.3	101.3	101.3	101.3	101.3	101.3	101.3	101.3	101.3	101.3
#2 (Nom. Watts)		0.	4	8.	12.	0	8	0	4	8	0	4	8	0.
Volts		-	6.018	8.514	10.4.2	-	8.511	-	6.018	8.511		6.016	8.511	-
Amps		-	.680	.962	1.177	-	.962	-	.680	.961		.68	.961	-
Watts		-	4.1	8.19	12.25	-	8.19	-	4.1	8.19	-	4.1	8.19	-
#3 (Nom. Watts)		0.	26.5	53.	79.50	0	53.	0	26.5	53.	0	26.5	53.	0
Volts		-	21.17	29.98	36.52	-	29.99	-	21.17	29.98		21.17	29.98	-
Amps		-	1.27	1.796	2.186	-	1.794	-	1.27	1.796		1.27	1.796	-
Watts		-	26.88	53.84	79.8	-	53.8	-	26.88	53.8	-	26.88	53.8	-
#4 (Nom. Watts)		0.	43.25	86.5	129.75	0	86.5	0	43.25	86.5	0.	43.25	86.5	0.
Volts		-	27.04	38.25	47.25	-	39.	-	27.0	39.		29.	29.	-
Amps		-	1.635	2.31	2.75	-	2.26	-	1.62	2.26		1.62	2.26	-
Watts		-	44.21	88.4	129.9	-	88.1	-	43.7	88.1	-	46.98	88.1	-
TC #'s	1	74.	74.	79.	81.	76.5	84.5	85.	87.	89.5	94.5	97.0	98.5	79.
	2	83.	85.	88	90.	86.0	95.	93.5	96.	99.0	103.	106.	108.0	89.
	3	75.	75.5	80.5	83.5	78.5	89.	86.	88.5	91.5	95.	99.0	100.5	80
	4	73.5	75.	80.5	84.5	77.	89.5	84.1	88.	91.5	94.	98.0	100.2	78.5
	5	73.5	75	81.0	85.0	77.	89.5	84.1	88	91.5	94.	98.5	100.5	78.5
	6	73.5	75	81.0	84.5	77.	89.5	84.1	88.	91.5	94.	98.0	100.2	78.

HP AUGMENTED COLD RAIL SYSTEM TESTS DATA, TESTS 1-13 (Sheet 2 of 2)

J.1 (con't	Test #:	1	2	3	4	5	6	7	8	9	10	11	12	13
T/C#	7	73.	72.5	78.	80.5	75.	84.	83.5	85.5	88.5	93.	96.	97.5	78.
	8	74	74.	78.5	81.5	76.5	86.	84.5	87.	89.5	94.	97.0	98.5	80.
	9	73.5	74.5	80	83.0	77.	88.	84.	87.2	90.5	94.	97.5	99.5	78.5
	10	73.	75.	81.5	85.0	77.	90.5	84.	88.3	92.0	94.	99.0	101.	78.5
	11	73	75.	81.5	85.0	77.	90.	84.	88.	92.0	94.	98.5	101.	78.5
	12	73.5	75.	81.5	85.0	77.	90.	84.	88.	92.0	94.	98.5	101.	78.5
HP Vapor	13	73.5	73.	77.0	79.0	76.	82.	83.5	86.	87.	92.5	95.5	96.0	78
	14	73.	75	80.5	84.0	77.	89.	84.	87.5	91.0	94.	98.	100.	78.
	15	73.5	74.5	80.	83.0	77.	89.	84.3	87.5	91.0	94	98.	100.	79.
	16	73.	74.5	80.	84.0	77.	89.	84.	87.5	91.0	94.	98.	100.	78.5
	17	73	74.5	80.	84.0	77.	89.5	84.	87.5	91.0	94.	98.	100.	78.5
Inlet	18	70.	68.	71.	71.5	69.	72.5	81.	81.5	82.0	90.5	91.	91.	71.5
	19	69.	67.	70.	70.	70.5	69.	80.	81.	80.5	90.0	90.5	89.	70.
Outlet	20	73.	74.5	80.	83	77.	79.	84.	87.5	90.5	93.5	97.5	99.	78.
	21	73.	74.5	80.	83	77.	79	84.	87.5	90.5	93.5	97.5	99.	78.
	22	73	74.5	79.5	82.5	77.	77.	84.3	87.5	90.5	94.	97.5	99.	79.
	23	73	75.	81.5	85.0	77.	80.	84.3	88.2	92.0	94.	98.5	101.	78
	24	80.5	81.	85.	88.	84.	83.	91.5	94.	96.5	101.	104.	105.	85.5
	25	87.5	88.	93	95.0	92.	100.	99.	100.5	103.0	108.5	110.	112.5	93.5
	26	75.	77	82	85.0	80.	90.	86.5	89.	92.0	96	99.	101.5	80.
	27	75	77.5	83.5	87.0	78.	91.5	85.5	89.5	93.5	96.	100.	103.5	80.5
	28	82.5	84	91.	95.0	86.	97.5	93.	97.5	102.0	102.5	107.	111.0	88.
Heater Plate	29	132.	134	136.	141.5	135.	145.	143.	145.	148.0	151.	154.5	157.0	137.
	30	140.	141.5	144.	148.5	143.	152.	150.	152.	155.5	158.5	161.	163.5	144.
	31	76.	80.	88.5	95.0	80.	97.	87.	93.	100.	96.	103.	109.	81.
	32	75.	78	87	93.0	78.	96.	86.5	91.2	97.5	96.	102.	107.	80.
	33	75.	78	85.5	91.5	78.5	95.	86.5	91.2	96.5	94.5	100.5	105.5	79.
	34	75.	78	85.5	91.0	80.	95.	86.5	91.2	96.5	95.0	100.5	105.5	79.
	35	75.	78	87.	93.0	78.5	96.	86.5	91.	97.5	95.	102.	108.0	79.5
	36	75	78.5	87.5	95.0	78.5	98.	86.5	92.	99.0	95.	102.	109.0	79.

HP AUGMENTED COLD RAIL SYSTEM TEST DATA, TESTS 14-26 (Sheet 1 of 2)

J.2 Test #:	14	15	16	17	18	19	20	21	22	23	24	25	26
Tinlet (Nominal)	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.	70.
Flow Rate #/Hr													
(Nominal)	40.	40.	80.	80.	40.	80.	80.	80.	80.	60.	60.	60.	60.
Actual	40.	40.	80.	80.	40.	80.	80.	80.	80.	60.	60.	60.	60.
# of Flow Passages	1	1	2	2	2	2	2	2	2	2	2	2	2
Heater Circuit													
#1 (Nom. Watts)	100	100	100	100	100	0.	4	8	12	100	100	100.	100.
Volts	30.16	30.16	30.16	30.16	30.16	-	6.03	8.52	10.412	30.15	30.15	30.15	30.15
Amps	3.36	3.36	3.36	3.36	3.36	-	.687	.961	1.177	3.36	3.36	3.36	3.36
Watts	101.3	101.3	101.3	101.3	101.3	-	4.10	8.19	12.25	101.3	101.3	101.3	101.3
#2 (Nom. Watts)	4	8	0	4	0	100	100	100.	100.	0.	4	8	12
Volts	6.02	8.51	-	6.02	-	30.01	30.01	30.01	30.01	-	6.02	8.514	10.419
Amps	.68	.961	-	.68	-	3.36	3.36	3.36	3.36	-	.68	.961	1.177
Watts	4.09	8.19	-	4.09	-	100.80	100.80	100.80	100.80	-	4.09	8.19	12.25
#3 (nom. Watts)	26.5	53.	0.	26.5	0.	0.	26.5	53.	79.50	0.	26.5	53	79.50
Volts	21.18	29.98	-	21.18	-	-	21.18	29.97	36.52	-	21.21	30.02	36.52
Amps	1.27	1.796	-	1.27	-	-	1.27	1.795	2.186	-	1.27	1.796	2.183
Watts	26.89	53.84	-	26.89	-	-	26.89	53.79	79.80	-	26.9	53.9	79.7
#4 (Nom. Watts)	43.25	86.5	0.	43.25	0.	0.	43.25	86.5	129.75	0.	43.25	86.5	129.75
Volts	27.5	39.0	-	27.5	-	-	27.5	38.6	47.25	-	27.0	39.0	27.25
Amps	1.54	2.26	-	1.54	-	-	1.54	2.24	2.75	-	1.62	2.26	2.75
Watts	42.35	88.1	-	42.35	-	-	42.35	86.47	129.9	-	43.7	88.1	129.9
T/C #'s 1	83.	88.	75.	76.5	78.	71.	74.5	76.0	77.	75.	76.	80.	82.
2	94.	100.2	86.5	86.5	89.	71.5	75.	77.5	79.2	84.	86.	90.	92.
3	85.2	91.5	77.5	78.5	81.	71.5	75.5	77.5	80.5	76.5	78.5	83.	86.
4	84.7	91.5	74.5	77.	78.	74.5	79.	81.5	85.	75.0	78.	83	87.
5	85.	92.	74.5	78.	78.	81.	85.	87.0	90.7	75.0	78.	83.5	87.
6	85.	91.5	74.5	78.	78.	76.	80.	83.0	86.5	75.0	78.	83.5	87.

HP AUGMENTED COLD RAIL SYSTEM TEST DATA, TESTS 14-26 (Sheet 2 of 2)

J.2 (con't)	Test #:	14	15	16	17	18	19	20	21	22	23	24	25	26
TC #	7	83.	88.5	74.0	76.	77.	71.	74.5	76.5	77.	74.	75.	79.	81
	8	85.5	92.	76.0	77.	79.	71.5	75.	76.5	78.	75.	76.	80.5	83
	9	84.	90.5	75.0	77.	79.5	71.5	76.	78.0	81.5	75.	77.	82.0	85
	10	85.	92.	74.5	77.5	78.	73.	78.	81.0	85.5	75.	78.5	84.	87.5
	11	85.	92.	74.5	77.5	78.	74.	78.5	81.5	85.5	75.	78.5	83.5	87.0
	12	85.	92.	74.5	77.5	78.	74.	79.	81.5	85.5		78.5	83.5	87.5
HP Vapor	13	83.	88.3	73.5	75.	76.	71.	73.	75.0	75.5		75.5	77.5	79.
	14	85	91.3	74.0	78.	78.	75.	79.	82.0	85.0		78.0	83.0	87.
	15	85	91.3	74.5	76.5	79.	72.	76.	79.0	82.		77.5	82.0	85.5
	16	84.	91.	74.0	76.5	78.	72.5	77.	80.0	83.		77.5	82.5	86.0
	17	85.	91.5	74.0	76.5	78.	73.	77.5	80.5	84.	75.	77.5	83.0	86.5
Inlet	18	72.5	73.5	71.0	70.5	72.	69.5	71.	71.0	71.	70.5	69.5	71.0	71.0
	19	70.5	70.5	70.0	68.	70.	69.	71.5	70.0	70.	69.5	68.5	69.0	68.5
Outlet	20	84.	90.	74.5	77.	78.	74.	78.	81.0	85.5	75.	77.5	82.	86.0
	21	83.5	90.	74.5	77.	78.	73.5	78.	81.0	85.5	75.	77.5	82.5	86.0
	22	84.	90.5	76.0	77.	79.5	71.	75.	77.5	79.5	75.	77.0	81.0	84.0
	23	85.	92.	74.5	78.	78.	74.	78.5	82.0	85.5	75.	78.5	83.5	87.5
	24	91.	96.	85.0	85.	98.	71.5	75.	77.0	78.	82.	83.5	87.0	89.5
	25	97.5	102.	76.0	93.	96.5	74.	77.	79.0	81	90.0	91.0	93.5	97.0
	26	85.7	91.	76.0	79.	80.	81.	82.5	86.0	88.5	77.0	79.0	83.0	87.0
	27	86.2	93.	76.0	79.5	79.	91.	95.	98.0	102.	76.0	81.0	85.0	89.5
	28	95.	102.	84.0	87.	87.	74.	79.	84.0	86.5	83.5	87.0	92.5	97.0
Heater Plate	29	142.5	148.	136.5	137.	139.	74.	78.5	83.0	86.5	134.0	136.0	140.	143.
	30	149.	154.5	143.	143.	145.5	73.5	78.5	84.5	89.	141.5	143.5	147.	150.5
	31	90.	99.	77.5	82.5	81.	74.	81.	87.0	94	77.0	83.5	91.	97.
	32	88.5	97.5	76.0	81.5	80.5	124.5	129.	132.5	135.	76.0	81.0	89.	95.
	33	88.5	96.2	76.0	81.5	80.5	123.5	128.5	129.5	135.	77.0	81.0	89.	95
	34	88.5	96.2	77.0	81.	80.5	83.5	89.	93.5	99.	77.0	81.0	89.	94.5
	35	88.5	97.	76.5	81.	80.5	72.5	81.	87.0	93.	76.5	81.0	89.	95.
	36	90.	98.3	76.5	81.5	80.5	72.5	81.	89.0	95.	76.5	82.0	91.	97.